Nutrient Dynamics and Water Quality Interactions in the Goose Creek Sub-Basin of the Charleston Harbor Estuary

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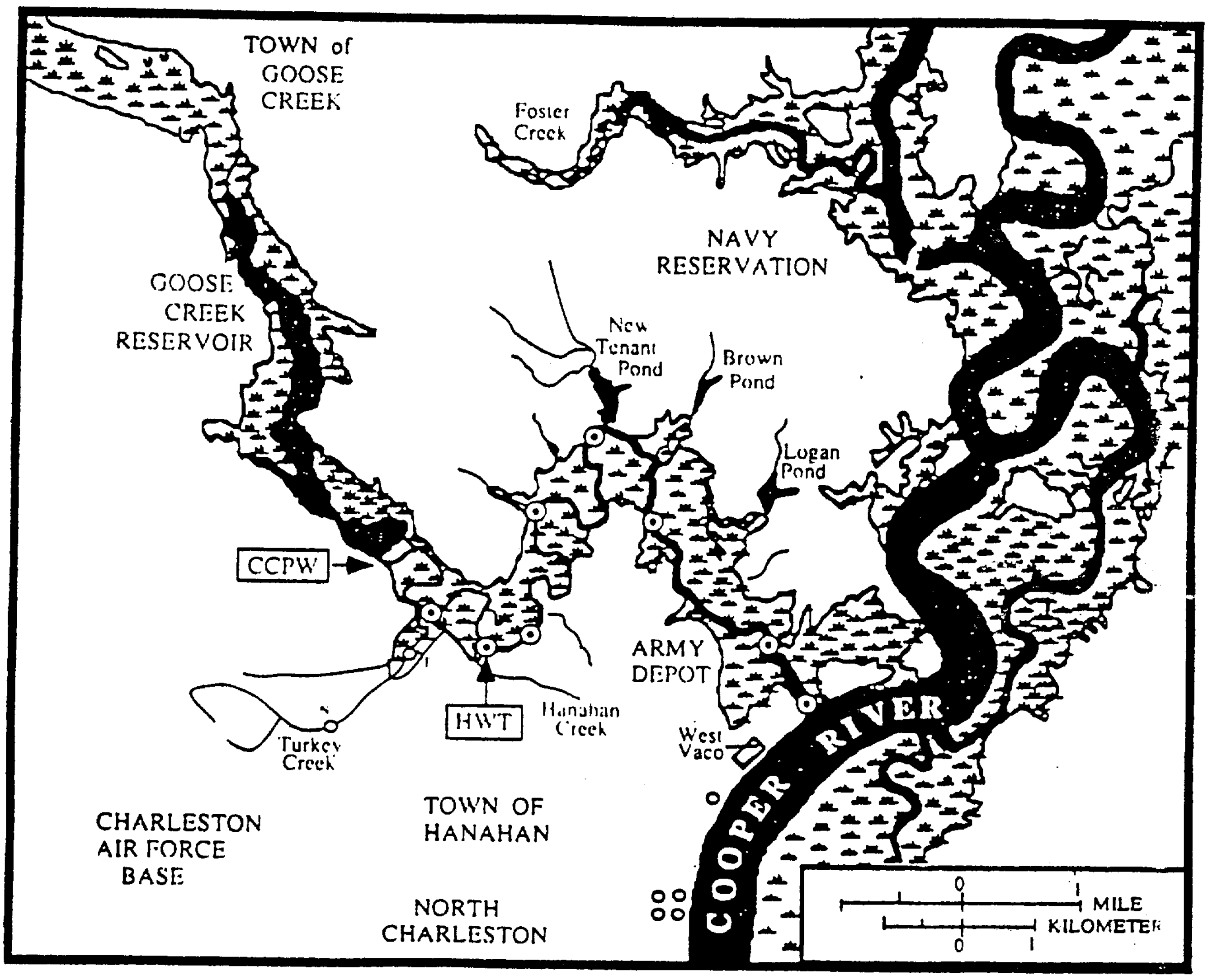

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ABSTRACT

Water quality in the Goose Creek estuary displayed distinct spatial and seasonal trends related to the location and timing of several key, interacting factors. Water quality conditions were most critical during the summer when higher temperatures and lower freshwater discharge led to an accumulation of nutrients, algal blooms and oxygen depletion. Nutrients increased during the summer with ammonium concentrations exceeding 100 µM in July. In response to higher nutrients, algal biomass increased to levels indicative of eutrophic conditions with chlorophyll concentrations exceeding 40 mg/l in the upstream reaches of the estuary. Dissolved oxygen fell below water quality standards (< 4 mg/l) throughout much of the estuary. Although this general pattern was part of a natural seasonal cycle, the severity of conditions was impacted by elevated nutrient loading from wastewater discharges and localized urban runoff. Maximum nutrient concentrations in the estuary occurred in the vicinity of the wastewater discharges and urban runoff. Minimum oxygen concentrations occurred several km downstream as oxygen demand from these sources was exerted.

The effects of wastewater discharge and stormwater runoff were mitigated by extensive tidal wetlands which removed and transformed nutrients during tidal inundation.. We found consistent trends of nitrogen uptake by the tidal marshes which removed 20-34% of the nitrate flowing across the marsh during each tidal cycle. Nitrate uptake by the wetlands exhibited a distinct seasonal pattern of daily removal ranging from 0.6-10.7 mg N/m^2 during the winter to 30-35 mg N/m^2 during summer and fall, yielding and annual uptake of 8.4 g N/m^2. Ammonium exchanges also suggested a tendency for net annual export (5.7/m^2/yr.) although values were more variable with no apparent seasonal pattern. Dissolved organic matter exchanges in the wetlands were also variable but displayed a strong tendency toward net export (57.3 g C/m^2/yr.). Algal biomass (chlorophyll-a) was exported from the marsh during the winter (0.1-0.8 mg/m^2/da) and imported during the late summer and fall (1.4-1.9 mg/m^2/da) yielding an approximate annual balance. The net removal of dissolved inorganic nitrogen by the tidal marshes (21.1 metric tonnes/yr) was a significant fraction of the overall nitrogen budget for the estuary and provided a buffer to potential impacts of point-source wastewater discharges as well as nonpoint urban runoff.

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INTRODUCTION

Water quality in urbanized estuaries is affected by a variety of inputs from human development including municipal and industrial wastewater discharges as well as nonpoint source urban runoff. These factors interact with a complex set of natural estuarine processes including freshwater runoff, tidal movements, and ecological functions in the water, sediments and wetlands. The combination of these influences form patterns of water quality change and distribution which must be understood for effective, long-term water quality management. The main goal of this study was to develop a better quantitative understanding of the controlling factors for water quality in an urbanized estuarine system.

As part of the Charleston Harbor project, this study focused on the Goose Creek estuary, a medium-salinity sub-basin of the Cooper River estuary (Fig. 1). The main estuarine channel extends approximates 16 km from the freshwater outflow of Goose Creek Reservoir to the Cooper River. Goose Creek joins the Cooper River estuary approximately 22 km upstream from Charleston Harbor, within the meso-haline region of the Cooper River estuary. The mouth of Goose Creek is approximately 125 m wide with a 8 m maximum depth. The channel narrows considerably toward its headwaters with a channel width less than 60 m and a maximum depth < 4 m. Tidal marshes form a .5-2 km-wide band of intertidal vegetation along the main channel, covering a total area of 6.8 km^2.

With a representative mix of urban, forest, and wetland influences (Table 1), findings from this study site may be extrapolated to larger scale issues throughout the Charleston Harbor/Cooper River system as well as to other urbanized estuaries of the southeastern US. The specific objectives of this study were to quantify dominant seasonal and spatial patterns of dissolved oxygen, nutrients (carbon, nitrogen, and phosphorus), and algal biomass and to evaluate the corresponding importance of

(a) seasonal changes in rainfall and freshwater stream flow,
(b) daily tidal exchange with intertidal wetlands,
(c) point-source wastewater discharges, and
(d) non-point source runoff from forested and urban watersheds.

STUDY PLAN AND METHODOLOGY

Temporal and Spatial Distributions

We sampled monthly at both high tide and low tide at 8 stations along a 16 km transect from the mouth of Goose Creek, upstream to the headwaters (outflow of the Goose Creek Reservoir, Fig. 1). Sampling was initiated in June 1992 and extended through November 1993. Sampling dates were usually within a few days of neap tides so that tidal mixing was minimized and spatial patterns within the estuary could be more easily quantified. One spring-tide phase was sampled on August 3, 1993. Dissolved oxygen, temperature, and salinity were measured *in situ* using YSI field meters (Mod. 55, 33, 3800). Water samples were collected using a weighted 1-liter polyethylene bottle with a 2.5-cm opening in the cap. The bottle was lowered to the bottom and retrieved through the water column to obtain a vertically mixed sample. Earlier investigations (Sicherman 1989) suggested very little vertical stratification at the mouth of Goose Creek with less than 0.5 o/oo median difference between surface and bottom salinity and less than 0.2 mg/l median difference in dissolved oxygen. Water samples were placed immediately in acid-washed polyethylene bottles and stored under ice. The samples were transported to Columbia where they were processed for analysis within 36 hours of collection. Samples were analyzed for dissolved inorganic nutrients (ammonium, nitrate, and ortho-phosphate), chlorophyll-a, and organic carbon. Detailed analytical and statistical procedures for trend analyses are outlined in Appendix A.

Contributing Sources

Along the main estuarine transect, additional samples were taken from the major contributing sources which included:

(a.) Goose Creek Reservoir, representing the major headwater input to the estuary, (Discharge from the reservoir was determined from a daily record of reservoir stage and a stage-discharge relationship developed for surface water overflow across the dam; Appendix B).

(b.) Point-source industrial discharges;

(1) Charleston Commissioners of Public Works (CCPW) which discharges effluent from drinking water processing into the upper estuary near the Reservoir dam. The effluent includes backwash from system filters and sludge pond overflow with total suspended solids frequently in excess of 200 mg/l. The NPDES permit for the facility is for 1.5 MGD average (2.3 cfs).

(2) the Town of Hanahan (HWT) which discharges municipal wastewater from an activated sludge, secondary treatment facility near the mouth of Hanahan Creek, 4.1 km downstream from the reservoir. The plant is permitted for 1.3 MGD (2 cfs) with 20 mg/l mean BOD. This nutrient-rich effluent (orthophosphate =5 mg/l, ammonia =3 mg/l, nitrate =8 mg/l) represented a significant nutrient source to the estuary.

(c). Tributary Inputs along the estuary, which represent largely nonpoint sources (NPS) of watershed runoff into the estuary from forested watersheds as well as from urban/residential watersheds.

(1) Forested Watersheds: Three tributary inputs from the Navy Reservation property on the north side of Goose Creek were selected as representative of forested watershed runoff in the study area (Table 1) Sampling stations were located at the outflows of New Tenant Pond, Brown Pond, and Logan Pond. An additional station was located at the upstream end (North end) of New Tenant Pond to examine inflow/outflow differences as an indication of impoundment influences on nutrient transport to the estuary.

(2) Urban/residential Watersheds: Three tributary inputs from the south side of Goose Creek were selected as representative of urban/residential watershed runoff to the study area. Two stations (Hanahan and Turkey Creeks) were located at the downstream juncture of the creeks with Goose Creek. Both of these stations were influenced by tidal action and samples were always taken within the hour of low tide to capture the maximum effect of watershed drainage into Goose Creek. A third "urban" station was located upstream on South Turkey Creek (STC) in a non-tidal section of the stream draining mostly commercial/urban sectors including much of the Charleston Air Force Base.. Since this station was non-tidal, runoff concentrations were less influenced by tidal mixing and more representative of direct "urban" runoff.

Storm flow Urban Runoff: Although a comprehensive examination of storm flow runoff was beyond the scope of this study, we did examine storm flow hydrology and nutrient runoff in one event at the South Turkey Creek station (Aug. 3, 1994). Before the storm event, base-flow conditions (discharge and nutrient concentrations) were measured daily for seven days (July 27-Aug. 3, 1994). Stream discharge was measured directly through detailed depth-velocity profiles at 6 stations across the double-channel culvert. Velocity was measured with an electromagnetic flow meter (Marsh McBirney). During the 0.4 inch thunderstorm, which occurred from 2000-2100 hours (Aug. 3), we examined discharge and nutrients for approximately 2 hours from peak discharge through the falling limb of the hydrograph.

Tidal Exchange and Nutrient Transport.

In addition to the monthly sampling for spatial and tidal distributions, we conducted intensive tidal transport studies of water exchange and nutrient flux at two key locations along the estuary.

(1) Browns Marsh is an 8.6 Ha. brackish water marsh (7-8 o/oo median salinity) located between Brown Pond and the main channel of Goose Creek (Fig. 1). This study site was used to evaluate nutrient exchange between tidal wetlands and the estuarine water. The marsh was dominated mainly by Smooth Cordgrass (*Spartina alterniflora*) with Black Needlerush (*Juncus roemerianus*), Giant Cutgrass (*Zizaniopsis mileacea*) and cattails (*Typha* spp) along the landward edges. Tidal water exchange between the marsh and the Goose Creek estuary was restricted to a single channel which passed through a rectangular culvert (1m high x 2m wide) facilitating accurate measures of tidal transport. Freshwater input from the upland side was easily measured in a discharge culvert leaving Brown Pond.

(2) the mouth of Goose Creek represented the interface between the Goose Creek sub-basin and the Cooper River estuary.

Tidal transport and mass flux studies were conducted over eight complete tidal cycles between February, 1993 and February, 1994. On each sampling date, depth and velocity profiles were measured across the tidal channel (3 to 5 stations) every 0.5 to 1.5 hours for 12.5-13 hours. Water velocity was measured with an electromagnetic velocity meter (Marsh McBirney) or a bucket-wheel flow meter (Price AA). For the main channel at the mouth of Goose Creek, we conducted two preliminary hydrologic studies to calibrate a one-dimensional hydrodynamic model (BRANCH, Schafffranek et al. 1981). After calibration and verification (Appendix C), the model was used in conjunction with tide stage recordings and detailed channel morphometry to compute velocity and discharge at this site for the tidal transport studies. At both sites, instantaneous discharge values (liters/sec) were integrated over the ebb and flood tides to compute the tidal prism (P) for each site and date. Freshwater discharge was typically < 10% of the tidal volume indicating that water movements were dominated by tidal exchange, even during the winter. For the eight tidal cycles, differences between ebb and flood tide volumes were usually less than 25% (median 12% net ebb for Browns Marsh and a median 13% net flood for the mouth of Goose Creek). The tidal prism for each site and date was calculated as the mean of the ebb and flood tide volumes.

Water samples were taken at the center of the channel every 2.5-3 hrs throughout each tidal cycle to determine concentration changes of carbon, nitrogen, and chlorophyll a. Mass transport rates for each constituent were computed as cross-products of water flow and concentration. Instantaneous flux rates were integrated over the tidal cycle to yield flow-weighted concentrations for the ebb flow (C_e) and the flood flow (C_f). The corresponding net mass exchange (E) for each water quality constituent was then computed as

$$E = (C_e - C_f)(P)$$

where positive values indicated a net export and negative values indicated a net import. Significant differences of (Ce-Cf) were identified with the Wilcoxon sign-rank test. Overall patterns of tidal exchange were summarized largely as median values and inter-quartile ranges (IQR = 50th percentile - 75th percentile). Outliers were designated as data points which differed from their nearest neighbor by more than 3(IQR).

RESULTS AND DISCUSSION

Freshwater Input

Freshwater input to the estuary displayed a distinct seasonal pattern (Fig. 2) which affected water quality and nutrient distributions. Input from the Goose Creek Reservoir dominated freshwater input for the year (> 90%), with peak monthly inflows (75-175 cfs) during the winter. However, a moderate drought during the spring and summer, resulted in a major reduction in reservoir discharge from May through December (0-10 cfs). During much of this time, point source wastewater discharges constituted 53-75% of the total freshwater input to the estuary. Monthly mean discharges from point source discharges were 1.5-2.5 cfs from the Town of Hanahan municipal wastewater (HWT) and 1.4-3.9 cfs from the Charleston Commissioners of Public Works drinking water processing plant (CCPW). Discharge from the domestic wastewater treatment plant was relatively consistent with slightly higher rates during the winter months. Discharge from the drinking water processing plant was more variable reaching peak rates in late July and early August (up to 7.4 cfs daily mean). These higher discharges occurred during a 2-week period when the sludge ponds were drawn down in anticipation of excessive rainfall during the hurricane season.

Water Quality Distributions and Contributing Sources

Water quality in the Goose Creek estuary displayed distinct spatial and seasonal trends. Summary concentrations of the water quality parameters are provided by season and estuarine region in Tables 2-5 with output for statistical trend analysis provided in Appendix D. Graphical representation of temporal/spatial trends and contributing sources are provided for each parameter in Fig.'s 3-25.

Water temperature exhibited a typical seasonal pattern for this area (Fig. 3), ranging from 9.6 ^{o}C in February 1993 to 30.7 ^{o}C in July 1993. There were no significant spatial differences between stations or regions of the estuary

Salinity varied from zero in the upper reaches to 14.6 $^{o}/oo$ at the mouth and displayed a significant negative correlation with freshwater discharge (Fig. 4 and 5).

During the peak freshwater discharge (January), salinity was depressed throughout the estuary, with high tide values less than 4 o/oo at the mouth. During late summer and fall, high tide salinity reached 14.6 o/oo near the mouth and up to 3 o/oo at the upstream station. Low-tide salinity reached levels of 0.5-2 o/oo in the upstream region during late summer and fall.

<u>Dissolved oxygen</u> concentrations varied widely from 2.7 mg/l in late July to 9.4 mg/l in late February (Fig. 6 - 8). This seasonal pattern showed a significant negative correlation with temperature, where lowest concentrations occurred during highest temperatures, consistent with lower oxygen solubility and higher rates of community respiration. The low concentrations in late July contravened water quality standards throughout the estuary. Lowest levels occurred at low tide (1000-1100 Hrs) in the middle and lower regions. This episode of oxygen depletion occurred during the initial stages of sludge pond draw down by the drinking water treatment facility in the upper region of the estuary (CCPW). Pond draw down began on July 20 and continued through early August with sustained discharges (> 4 cfs) approximately twice normal discharge). During the first week of draw down, this effluent had elevated concentrations of ammonia (52 mg-at/l) and organic carbon (400 mg/l) which could have contributed to the estuarine oxygen demand and depletion. The domestic wastewater discharge also had elevated ammonia levels during July (765 mg-at/l) with corresponding effects on nitrogenous oxygen demand.

Significant regional differences in dissolved oxygen occurred only during the summer when concentrations in the upper estuary were consistently higher than in the middle and lower regions. Tidal patterns displayed a consistent oxygen sag in the middle of the estuary during high tide and in the lower region during low tide. Although effluents from the point source discharges were usually well oxygenated (5-10 mg/l annual mean), contributing to higher oxygen concentrations in the upper regions, their oxygen demand (both carbonaceous and nitrogenous) probably influenced oxygen sag in the middle and lower regions of the estuary. Inputs from forested watersheds (and associated forested wetlands) along the middle region of the estuary may also have contributed some to the lower oxygen concentrations in this area. Summer discharge from these tributaries were characterized by low oxygen concentrations (often <4 mg/l). However, due to drought conditions during the summer, stream flow in these tributaries was considerably diminished and often intermittent. Under these conditions, it was unlikely that runoff from forested watersheds contributed to the low estuarine oxygen concentrations.

Orthophosphate concentrations varied from 0.3 to 5.3 μg-at/l with an overall 15-month mean of 1.3 ± 0.1 μg-at/l (Fig. 9 and 10). In general, higher concentrations (> 2 μg-at/l) occurred during the summer and fall although seasonal patterns were not statistically significant. Significant regional differences emerged only during the summer when concentrations near the mouth (lower estuary) were 26 to 39 % higher than in the upper oligohaline region of the estuary. This pattern was particularly evident during high tides indicating a major flood tide influence from the Cooper River on the orthophosphate distribution in Goose Creek. Although concentrated inputs from municipal wastewater discharges (160 ± 63 μg-at/l annual mean, Fig. 11) caused locally elevated concentrations at the point of discharge in the upper estuary (Fig. 10), this influence did not affect broader regional differences. Overall mean concentrations in other contributing sources ranged from a low of 1.0 ± 0.2 μg-at/l from the drinking water processing plant (CCPW) to a high of 2.4 ± 0.6 μg-at/l from the Goose Creek Reservoir. During base-flow conditions, input concentrations from urban runoff (1.2-1.8 μg-at/l were not significantly different from concentrations in forest runoff (1.4-1.7 μg-at/l). However, during storm runoff, orthophosphate concentrations increased considerably during the falling stages of the hydrograph (Fig. 19). The computed flow-weighted storm concentration (3.4 μg-at/l) was more than 3-fold higher than during pre-storm base flow conditions (1.0 ± 0.1 μg-at/l).

Ammonium concentrations were highly variable, ranging from 1 to 138 μg-at/l with a mean of 9.7 ± 1.0 μg-at/l and a median of 5.3 μg-at/l (Fig. 12,13). Peak concentrations (> 100 μg-at/l) occurred in July and August 1993 and were significantly higher than during other months. Although estuarine ammonium levels are expected to increase during the summer due to temperature enhanced remineralization rates, these extreme levels suggest impact from external sources. Combined summer data (1992-93) indicate a local peak within the estuary adjacent to the municipal wastewater discharge (kilometer 12.2) which exhibited maximum effluent ammonium concentrations (> 700 μg-at/l). This effluent ammonium concentration was > 3-fold higher than annual means concentrations in the effluent (Fig. 14). Furthermore, effluent from the drinking water processing plant (CCPW) also exhibited its maximum ammonium levels in July (52.3 μg-at/l) which were also >3-fold higher than annual mean discharge effluent concentrations. These elevated concentrations in combination with higher discharge flow rates in July and August (related to sludge pond draw down) further suggest impacts from this point source.

Urban runoff may also have affected local distributions of estuarine ammonium. Average base-flow concentrations in urban runoff (18-25 μg-at/l, Fig. 14), was 2-3-fold higher than mean estuarine concentrations. Peak ammonium concentrations in urban storm runoff approached 100 μg-at/l during the falling stage of the storm hydrograph (Fig. 19).

Nitrate concentrations ranged from 1 to 49.5 μg-at/l with a mean of 11.9 ± 0.5 μg-at/l for the study period. Nitrate displayed a significant seasonal pattern with higher concentrations in the late summer and fall (Fig. 15). As for the other inorganic nutrients, warmer temperatures are expected to stimulate nutrient remineralization rates resulting in higher concentrations during the warmer months. Nitrate loading from municipal wastewater clearly affected spatial patterns within the estuary. During the summer, nitrate was significantly higher in the upper estuary (14.3 ±1.3 μg-at/l) with peak concentrations (> 20 μg-at/l) nearest the municipal wastewater outfall at high tides (Fig. 16). At low tide, this peak was displaced downstream resulting in significantly higher concentrations in the middle region of the estuary (Fig. 17). The overall mean nitrate concentration in municipal wastewater discharge varied widely from 111 to 1583 μg-at/l with a 15-month mean of 570 ± 110 μg-at/l (Fig. 18).

Base-flow runoff from urban watersheds was also significantly higher in nitrate than forest runoff (Fig. 18) suggesting further impacts on nitrate distributions from NPS urban runoff. Non-tidal urban runoff, indicated by South Turkey Creek (STC) was > 3 times more concentrated than average estuarine water and > 10 times more concentrated than the mean runoff from forested watersheds. During storm flow runoff, nitrate concentrations in the urban drainage were slightly diluted with flow-weighted concentrations 20% lower than during base-flow conditions (Fig. 19). Even with storm flow dilution, urban runoff was still almost 3 times more concentrated in nitrate than average estuarine water, suggesting potential localized nonpoint source impacts from urbanized watersheds.

Chlorophyll-a, as an indicator of algal biomass, varied in the estuary from < 0.5 μg/l in winter to > 100 μg/l in summer with significant summer peaks, especially in the upper region (Fig. 20 and 21). Regional differences were particularly pronounced in both fall and summer when mean concentrations in the upper estuary were > 4 times higher than in the lower estuary. Concentrations >40 μg/l (indicative of eutrophic, bloom conditions) occurred in 40% of the total summer observations in the upper estuary. The elevated algal biomass in the upper estuary was due largely to estuarine algal production rather than import from contributing sources. Although the headwater source (Goose Creek Reservoir) had substantial concentrations of chlorophyll-a (Fig. 22), summer time discharge from the reservoir was diminished due to drought conditions and was not a major input to estuarine algal biomass. In addition, summer chlorophyll in the upper estuary (30-40 μg/l) was consistently higher than in the input waters from the reservoir (16-25 μg/l) further indicating the importance of estuarine algal production. Tributaries from forested watersheds also contained relatively high concentrations of chlorophyll-a (12-18 μg/l, annual mean, Fig. 22) due, in part, to algal production in upstream impoundments. However, due to diminished discharge during the summer it was unlikely that these inputs affected estuarine chlorophyll distributions. Urban runoff (STC) and point source effluents (HWT, CCPW) contained low concentrations of chlorophyll-a (Fig. 22), although their role as nutrient sources was probably important in stimulating estuarine algal production.

Organic Carbon in the estuary was dominated by dissolved organic matter which typically composed 73-92 % to the total organic carbon content in the water. Dissolved organic carbon (DOC) displayed significant seasonal and spatial trends (Fig. 23 and 23) related largely to freshwater input. Highest mean concentrations occurred during high freshwater discharge (winter) in the upper estuary (13.2 ± 1.1 mg/l) and lowest concentrations occurred in fall in the lower estuary (3.6 ± 0.3 mg/l). The spatial pattern of decreasing concentrations from the headwaters to the mouth was evident throughout the year with the downstream stations 35-45% lower than upper stations (Fig. 23). Concentrations were usually higher at low tide except during the winter when salinity was lowered throughout the estuary. In contrast to point source impacts on nutrient distributions, the two point source effluents typically had lower DOC concentrations than other contributing sources (Fig. 25). The other contributing sources (including the Goose Creek Reservoir, forested watersheds, and urban watersheds) were similar although the highest mean values were for the forested watersheds.

Tidal Exchange and Nutrient Transport

Browns Marsh

The tidal creek draining the 8.6 Ha. Brown Pond marsh exhibited tidal ranges from 140 to 182 cm with a median range of 157 cm. (Table 6). Creek depths ranged from <5 cm at low tide to almost 200 cm at high tide with median depths of 29 cm and 189 cm, respectively. The regular tidal fluctuations corresponded to tidal prisms ranging from 10 x 10^6 l/tide (Feb. 1993) to 40.8 x 10^6 l/tide (Nov. , 1993) with a median value of 29 x 10^6 l/tide. Figure 26 demonstrates a typical pattern of tide stage and flow during a tidal cycle analysis at the marsh study site. Although we had no direct measures of percent inundation of the tidal marsh, anecdotal information suggests that most of the marsh surface was flooded during each semi-diurnal high tide. This regularity of marsh inundation is probably a dominant feature of marshes along the southeast coast. In the marshes of the Chesapeake Bay, where much information on tidal nutrient exchange has been gathered (Axelrad et al. 1976, Heinle and Flemer 1976, Wolover et al. 1983, Jordan et al. 1983, Jordan and Correll 1991), tidal ranges are smaller (< 50 cm) and highly irregular, dependent largely on seiches in the bay and wind speed and direction (Jordan and Correll 1991). Similar irregularities are characteristic of micro tidal marshes along the Gulf of Mexico where other nutrient exchange studies have been conducted (Childers and Day 1988).

In response to regular, extensive tidal inundation, the Brown Pond marsh exhibited significant patterns of nutrient exchange. The dominant pattern was a consistent net import of nitrate to the marsh. The typical pattern of nitrate changes during a tidal cycle (Fig. 27) exhibited significantly higher concentrations during flood tides than during ebb tides ($p \leq .016$), reflecting a net removal of nitrate from tidal waters. Over the eight tidal cycle studies, we found consistent trends of nitrate uptake by the tidal marshes which removed 20-34% of the nitrate flowing across the marsh during each tidal cycle (Fig. 28). Nitrate uptake by the marsh also exhibited a distinct seasonal pattern ranging from 2-34 moles/tide during the winter to 83-112 moles N/tide during the summer and fall. Considering the 8.6 Ha. of marsh surface (and assuming a 12.47-hr tidal period) these values correspond to winter uptake rates of 0.6-10.7 mg N/m^2/day and summer-fall rates of 30-35 mg N/m^2/day. Using linear extrapolation for months with missing data, this seasonal pattern yielded an annual rate of nitrate removal of 8.4 g N/m^2.

Nitrate removal by tidal wetlands has been well documented in the literature (Valiela and Teal 1979, Nixon 1980, Whiting et al. 1989, Rivera-Monroy and Twilley 1996) with uptake attributed to microbial denitrification in the anaerobic marsh sediments, uptake by the shallow roots of marsh vegetation, retention by decomposing organic matter in the sediments. The seasonal pattern nitrate uptake exhibited in Browns Marsh was consistent with that found by Whiting et al. (1989) who found higher rates during the summer in the high salinity salt marshes of Bly Creek, North Inlet (SC). The Bly Creek study further demonstrated a linear relationship between rates of nitrate uptake by the marsh and nitrate concentrations in flood waters. This relationship could help explain the overall higher annual rates of nitrate uptake observed in the Browns Marsh. In Bly Creek, as in other marsh systems where tidal nutrient dynamics have been documented, floodwater concentrations of nitrate were generally < 2 μM, with annual uptake rates of 0.3-2.2 g N/m^2/yr. Floodwater concentration in the Brown Pond marsh were considerably higher (9-17 μM), resulting in part from local wastewater discharges. The high rates of nitrate uptake by Browns Marsh could reflect a direct response of the marsh system to increased floodwater concentrations, representing an important role of marshes as nitrate buffers in urbanized, eutrophic estuaries.

Ammonium exchanges were more variable with less apparent seasonal pattern (Fig. 29) although net export tended to occur during the winter and spring; and net uptake during the summer and fall. The extreme export value observed in May (> 2000 moles/tide) was a statistical outlier although based on a clear trend of rising ammonium concentrations during ebb flow as the marsh surface drained. During the year, the marsh exported ammonium on 5 of the 8 tidal cycles with an inter-quartile range of values (-2 to 98 mg N/m^2/da) suggesting a tendency for net annual export (5.7 g N/m^2/yr. based on a median daily rate of 15.7 mg N/m^2/da.). This result is consistent with much of the literature which document annual ammonium export from tidal marshes (Valiela and Teal 1979, Jordan et al. 1983, Whiting et al. 1985, Jordan and Correll 1991). Even though the vegetated surface of the marsh may remove ammonium from tidal waters due to microbial and plant uptake during the growing season (Valiela and Teal 1979, Wolaver et al. 1983, Whiting et al. 1989), ebb tide drainage of the marsh surface entrains high concentrations of ammonium from interstitial pore waters often leading to a net annual ammonium export from the marsh system. Furthermore, ammonium-rich interstitial water is advected and diffuses through the bottom of tidal creeks, contributing to ammonium export from the marsh system (Whiting and Childers 1989).

Even with the export of ammonium, the high rate of nitrate uptake by Browns Marsh yielded a net removal of dissolved inorganic N (DIN = ammonium + nitrate) of 3.1 g N/m^2/yr. If all of the tidal marshes in the Goose Creek basin (6.8 km^2) remove nitrogen at this rate, then the marshes take up approximately 21 metric tonnes of DIN. This amount is approximately equivalent to the total DIN discharged to the Goose Creek estuary by point source effluents (see footnote a and b). Even if both organic and inorganic N are accounted for (footnote c and d), this rate of DIN removal by the marshes clearly represents an important component of N cycling and may play a critical role in buffering the estuary from municipal and industrial discharges.

Dissolved organic carbon exchanges in the marsh were also variable, ranging between import in the spring to export in the fall and winter (Fig. 30). Even though the largest exchange (-137 kg/tide) was the spring import, the marsh exported DOC during 5 of the 8 tidal cycles and displayed an inter-quartile range (0-38 kg/tide) which indicated a strong tendency for net annual export (57.3 g $C/m^2/yr$). Almost all marsh systems export DOC (Nixon 1980, Jordan et al. 1983, Dame et al. 1991) at rates from 8 to 140 g $C/m^2/yr$, representing a potential carbon source for estuarine microbes.

Tidal exchanges of chlorophyll-a varied between 63 g/tide import and 263 g/tide export (Fig. 31). The extreme export value found in August was probably an artifact caused by a missing sample. Chlorophyll concentrations during maximum ebb flow during the August sampling were extrapolated from unusually high concentrations observed during diminishing ebb flow near low tide. Although these concentrations were probably accurate, it is unlikely that corresponding extrapolations were representative of concentrations during maximum ebb flow. This extreme flux value was clearly a statistical outlier. If the outlier is removed, the remaining values suggest a seasonal pattern of summer import and winter export of algal biomass, yielding an approximate annual balance (0.01 g chlorophyll/m^2/yr.). This temporal pattern in tidal exchange may reflect seasonal changes algal production on the marsh sediments. During the summer, marsh macrophytes shade the sediment substrate, inhibiting high production rates of marsh sediment algae. With increased phytoplankton in the estuarine water during the summer, the marsh acts more as a sink for floodwater chlorophyll. However, during the winter, estuarine phytoplankton have diminished and the marsh sediment is less shaded by macrophytes. During this time, the marsh is more conducive to sediment algal production and chlorophyll export with tidal exchange.

Mouth of Goose Creek/Total System Mass Balance

Hydrology at the mouth of Goose Creek was characterized by a median tidal range of 161 cm and a median tidal prism of 2.6 x 10^9 l/tide (Table 6). Table 7 lists the computed flow-weighted concentrations and net tidal exchange for the major constituents measured in this study.

Dissolved inorganic nitrogen (nitrate+ammonium) was exported from the Goose Creek estuary to the Cooper River largely as nitrate. The flow-weighted ebb concentrations of nitrate were usually greater than flood tide concentrations ($p = .078$)

Based on: (a) annual mean wastewater discharges from HWT (2.1 cfs) and CCPW (2.2 cfs) (b) annual mean DIN in HWT (772 µM) and CCPW (27 µM) effluents, (c) total organic carbon in HWT (13.6 mg/l) and CCPW (16.1 mg/l) effluents, and (d) an assumed ratio of 5.7 C:N (by weight) in wastewater effluent.

yielding a net nitrate export during 5 of the 7 tidal cycles studied (Table 7). The inter-quartile range of exchange values displayed a strong tendency toward export with a median value of 23.2 kg/tide. On the other hand, ammonium exchanges varied widely and the inter-quartile range of values broadly overlapped zero, suggesting little contribution to the DIN export from the estuary.

Figure 32 places these computed exchanges at the mouth of Goose Creek in the context of an annual mass balance in relation to measured values for point source discharges, nonpoint source runoff, and wetland exchanges. Annual loading from point sources was computed as the product of the mean discharge and the mean constituent concentration (see footnote on previous page). Similarly, the annual from the Goose Creek Reservoir and nonpoint source runoff from other local watersheds was calculated from mean discharge and the mean constituent concentrations. The annual freshwater discharge from local watersheds was computed from monthly water budget estimates considering recorded precipitation and evapotranspiration (Thornthwaite and Mather 1957). Mean concentrations from forested watersheds were based on the 3 routine sampling sites (2 sites on the New Tenant stream and 1 site at the Brown Pond outflow). Concentrations for "urban" watersheds were based on routine measurements in South Turkey Creek (other "urban" streams (North Turkey and Hanahan) were tidally influenced and less representative of direct runoff from urban areas). Internal sources and sinks (production, remineralization, and consumption) were computed to balance the mass budget determined from these measured processes.

The largest measured input of DIN to the estuary was from point source discharges, primarily from the Hanahan wastewater treatment plant (Fig. 32). The nonpoint source contribution from local watersheds (5.5 MT/yr) was dominated by export from urban runoff (85%). The average DIN concentration in urban runoff (66 μM) was 5 times higher than DIN in forested runoff (12.8 μM). The measured DIN uptake by the tidal marshes was equivalent to the point source discharge and represented a major component of the total DIN budget. The observed net export from the estuary (16.3 MT/yr.) required an internal source of DIN (7.6 MT/yr.) probably from remineralization of organic inputs from the Goose Creek Reservoir, point sources, and wetlands.

Algal biomass was consistently imported from the Cooper River to the Goose Creek estuary .(Fig. 32). Flow-weighted flood tide chlorophyll concentrations were consistently greater than ebb tide concentrations ($p = .055$) yielding a median net import of 1.09 kg chlorophyll-a/tide (Table 7) or 0.77 metric tonnes/yr. Discharge from the Goose Creek Reservoir represented another significant input of algal biomass to the estuary where other nonpoint sources from local watersheds, point source discharges and tidal exchange with the marshes represented minor additions (Fig. 32). With these physical inputs of algal biomass to the estuary in addition to internal phytoplankton production (not addressed in this study), a chlorophyll mass balance requires substantial quantities of algal consumption within the estuary (zooplankton grazing and benthic filter feeding). Apparently, such mechanisms were efficient in utilizing internal algal production on an annual basis, although chlorophyll tended to reach eutrophic levels (20-40 µg/l) in the upper estuary during the summer.

Dissolved organic carbon was probably exported on an annual basis from the mouth of Goose Creek although imports occurred on 3 of the 8 tidal cycles measured (Table 7). The inter-quartile range of export values showed a substantial tendency toward net annual export with a median value of 1.34 metric tonnes/yr. Extrapolating this value throughout the year indicates a large export of DOC from the estuary, responding in part, to major inputs from the Goose Creek Reservoir and export from the tidal marshes (Fig. 32). An annual mass balance for DOC would require additional internal production of DOC (leaching and recycle from particulate matter inputs and primary production). However, these processes do not appear to play as large a role in the DOC budget as freshwater inflow and marsh export (Fig. 32).

SUMMARY AND RECOMMENDATIONS

Water quality in the Goose Creek estuary displayed distinct spatial and seasonal trends related to the location and timing of several key, interacting factors. Water quality conditions were most critical during the summer when higher temperatures and lower freshwater discharge led to an accumulation of nutrients, algal blooms and oxygen depletion. Nutrients increased during the summer with ammonium concentrations exceeding 100 µM in July. In response to higher nutrients, algal biomass increased to levels indicative of eutrophic conditions with chlorophyll concentrations exceeding 40 µg/l in the upstream reaches of the estuary. Dissolved oxygen fell below water quality standards (< 4 mg/l) throughout much of the estuary. Although this general pattern was part of a natural seasonal cycle, the severity of conditions was impacted by elevated nutrient loading from wastewater discharges and localized urban runoff. Maximum nutrient concentrations in the estuary occurred in the vicinity of the wastewater discharges and urban runoff. Minimum oxygen concentrations occurred several km downstream as oxygen demand from these sources was exerted.

In many respects, the Goose Creek sub-basin is representative of other major tributary sub-basins such as the Ashley and Wando Rivers. . Although the Cooper River forms the main hydrologic axis of the Harbor system, the tributary sub-basins and their associated wetlands form a large portion of the Charleston Harbor estuary. These sub-basins typically receive very little freshwater input (especially during the summer months) causing them to be more sensitive to oxygen depletion and eutrophication. With this level of areal importance and potential sensitivity to BOD and nutrient loading, these systems may require more frequent monitoring and more limited wasteload permit allocation.

The effects of wastewater discharge and stormwater runoff may be mitigated, in part, by extensive tidal wetlands which remove and transform nutrients during tidal inundation.. We found consistent trends of nitrogen uptake by the tidal marshes which removed 20-34% of the nitrate flowing across the marsh during each tidal cycle. Nitrate uptake by the wetlands exhibited a distinct seasonal pattern of daily nitrogen uptake ranging from 0.6-10.7 mg N/m^2 during the winter to 30-35 mg N/m^2 during summer and fall. Ammonium exchanges suggested a tendency for net annual export (6-16 mg $N/m^2/da$) although values were more variable with no apparent seasonal pattern. Dissolved organic matter exchanges in the wetlands were also variable but displayed a strong tendency toward net export (157 mg $C/m^2/da$). Algal biomass (chlorophyll-a) was exported from the marsh during the winter (0.1-0.8 $mg/m^2/da$) and imported during the late summer and fall (1.4-1.9 $mg/m^2/da$) yielding an approximate annual balance. The net removal of dissolved inorganic nitrogen by the marshes was a significant fraction of the overall nitrogen budget for the estuary and provided a buffer to potential impacts of point-source wastewater discharges as well as nonpoint urban runoff.

With this magnitude of nutrient exchange and transformation, the tidal marshes of the Charleston Harbor (and other similar estuaries) clearly need to be accounted for in nutrient balance and analyses and in wasteload allocation models. Whereas we found consistent patterns of nitrate removal by mesohaline marshes, we still need more detailed information on wetland exchange patterns for BOD, organic matter, and ammonia over longer term a wide range of wetland salinity zones (including tidal freshwater).

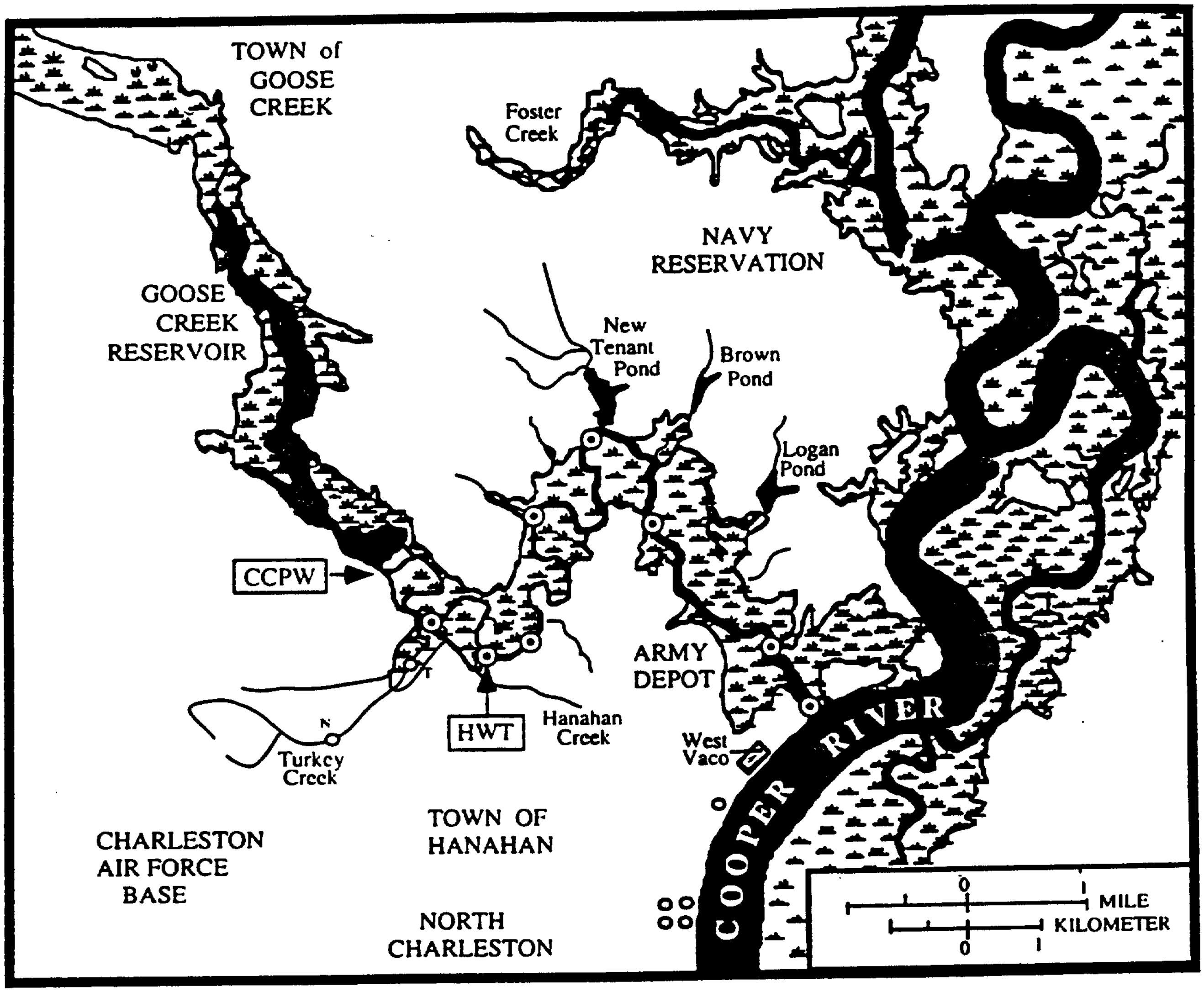

Figure 1. **The Goose Creek Sub-basin of the Cooper River Estuary.** Circled dots indicate sampling stations along the main channel. Open circles indicate sampling stations along Turkey Creek tributary, one upstream on a non-tidal reach, N (Rivers Avenue) and one on a tidal section, T (Murray St. Bridge). CCPW indicates the Charleston Commissioners of Public Works (Drinking water processing effluent); HWT indicates the Town of Hanahan wastewater treatment effluent. Other sampling stations are described in the text.

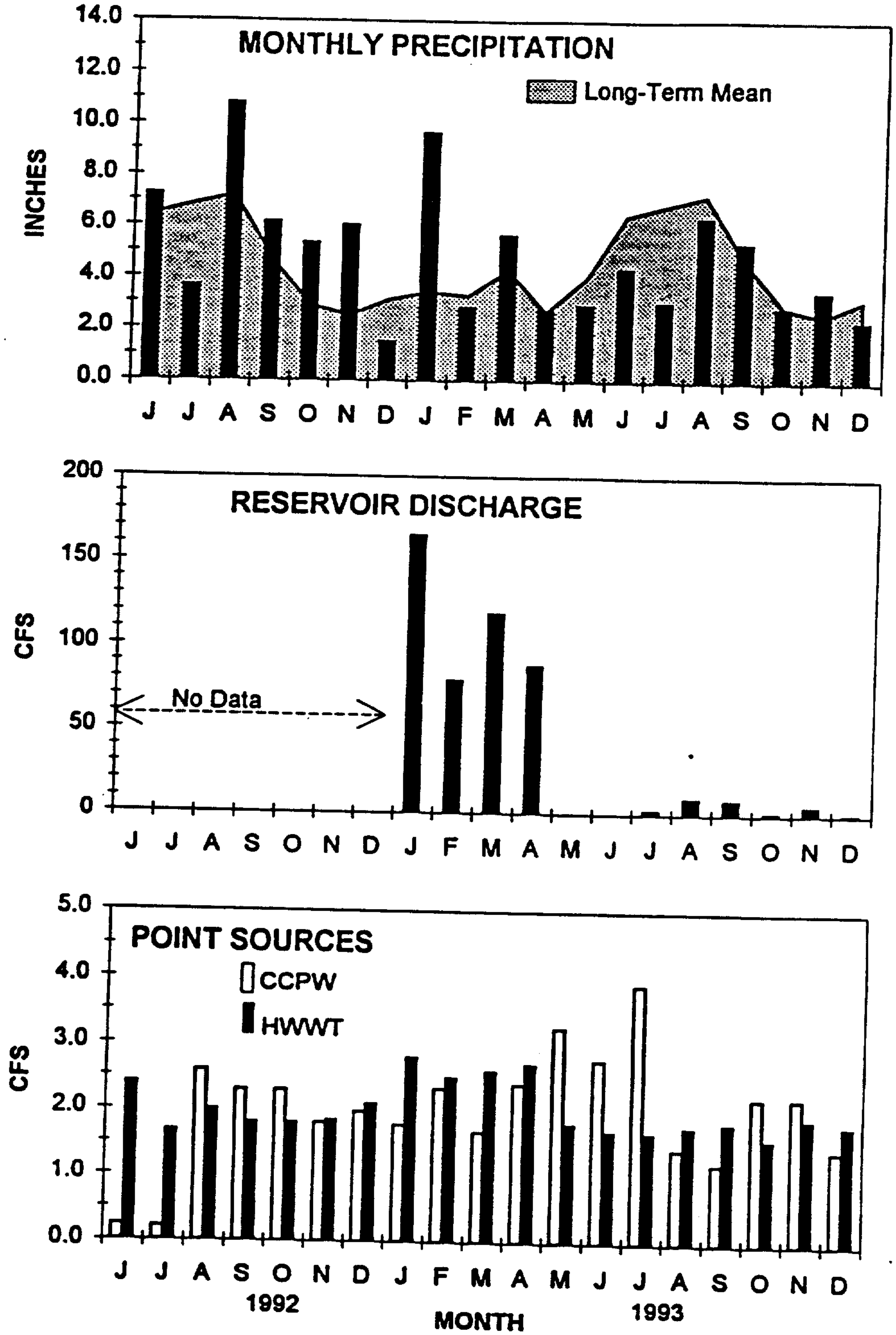

Figure 2. **Monthly precipitation, reservoir discharge , and point source discharges into the Goose Creek estuary.** Rainfall data were provided by the National Weather Service for the Charleston Airport (long-term means) and by the Charleston Commissioners of Public Works (CCPW) for the Goose Creek headwaters (1993). CCPW effluent is filter backwash and sludge pond overflow from drinking water processing. HWWT is the Hanahan domestic wastewater treatment facility (activated sludge).

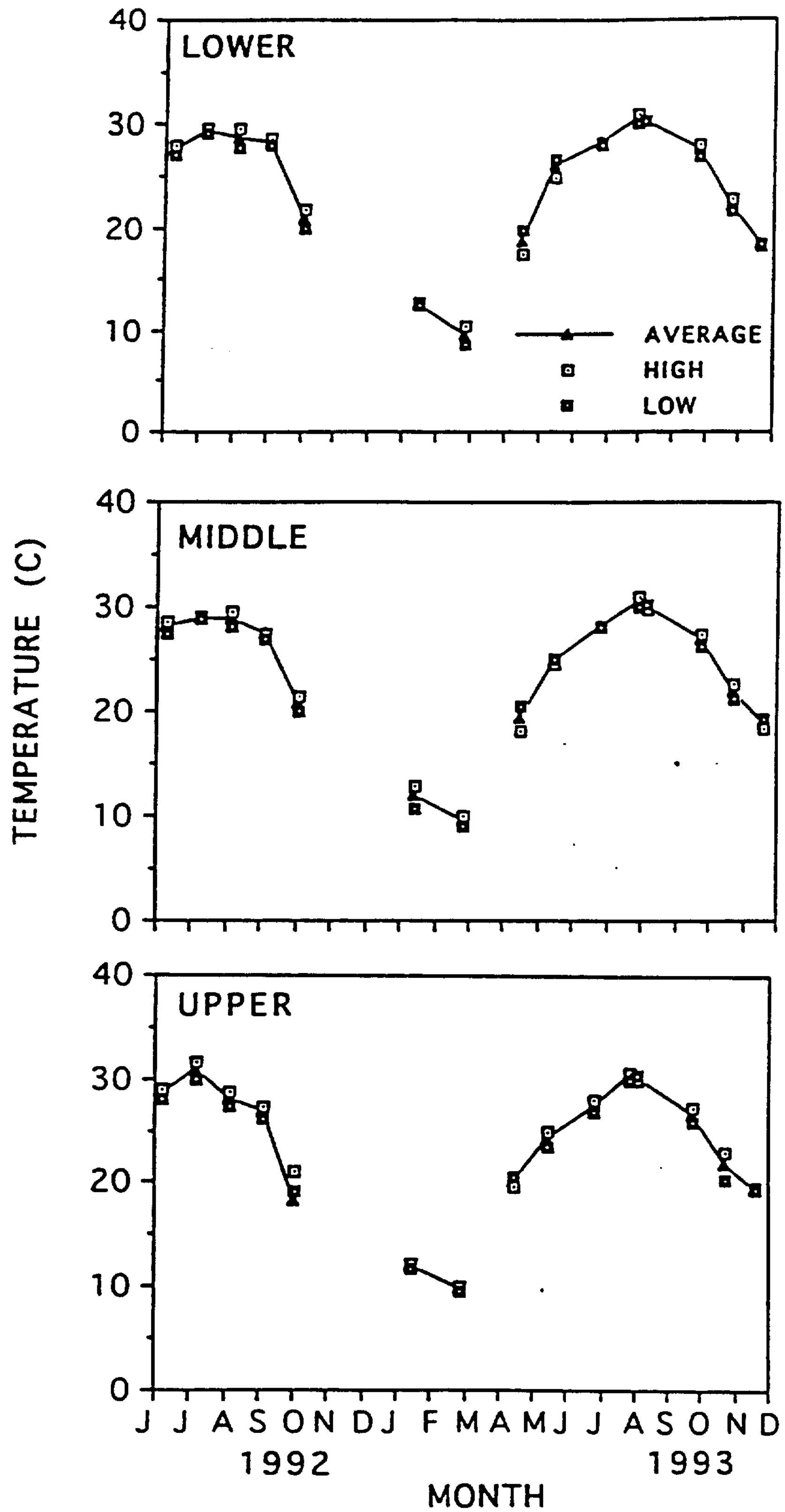

Figure 3. **Seasonal patterns of water temperature in the Goose Creek estuary by region. Triangles indicate monthly means over high and low tides. Open squares indicate monthly means at high tide. Closed squares indicate monthly means at low tide.**

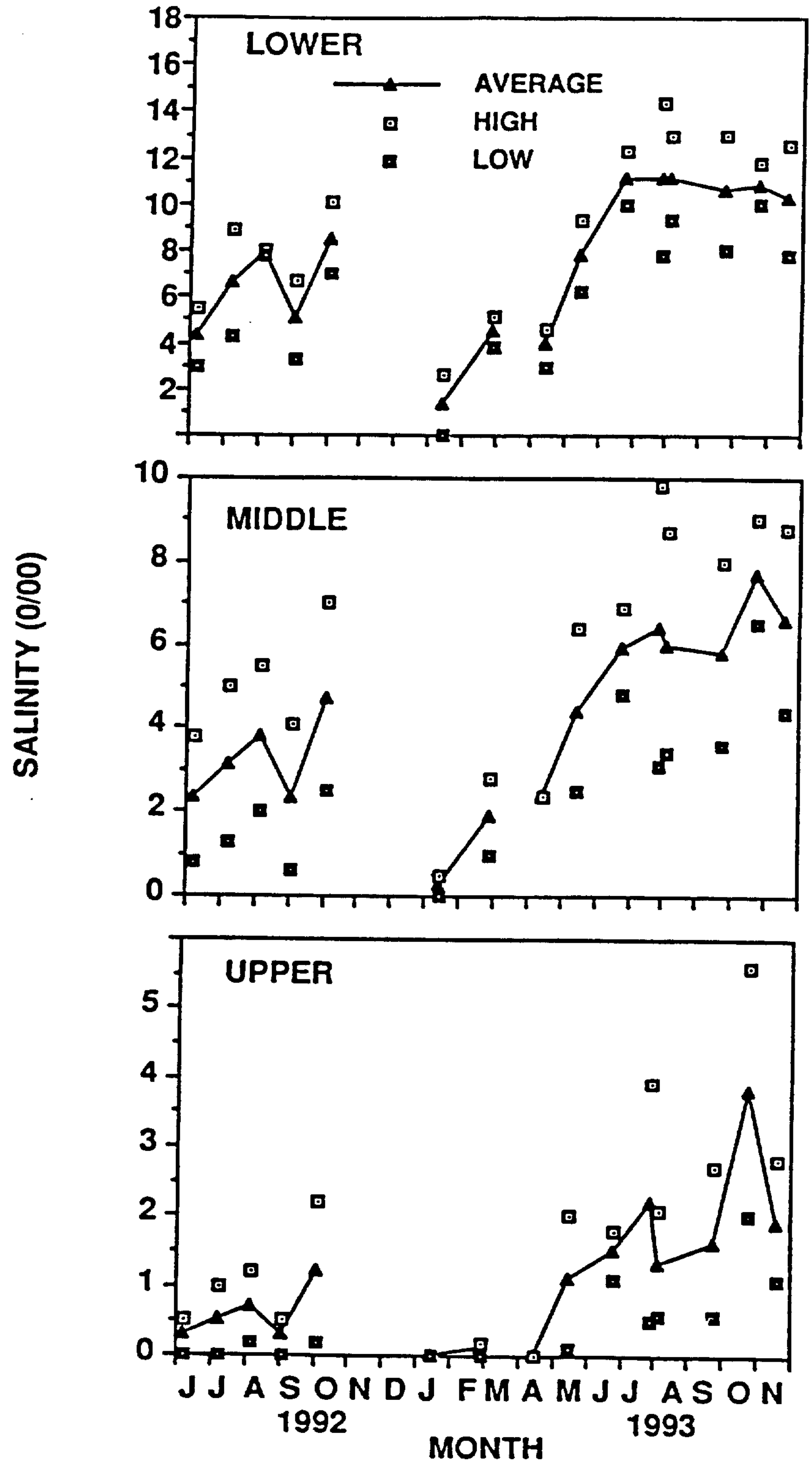

Figure 4. **Seasonal patterns of salinity in the Goose Creek estuary by region.**

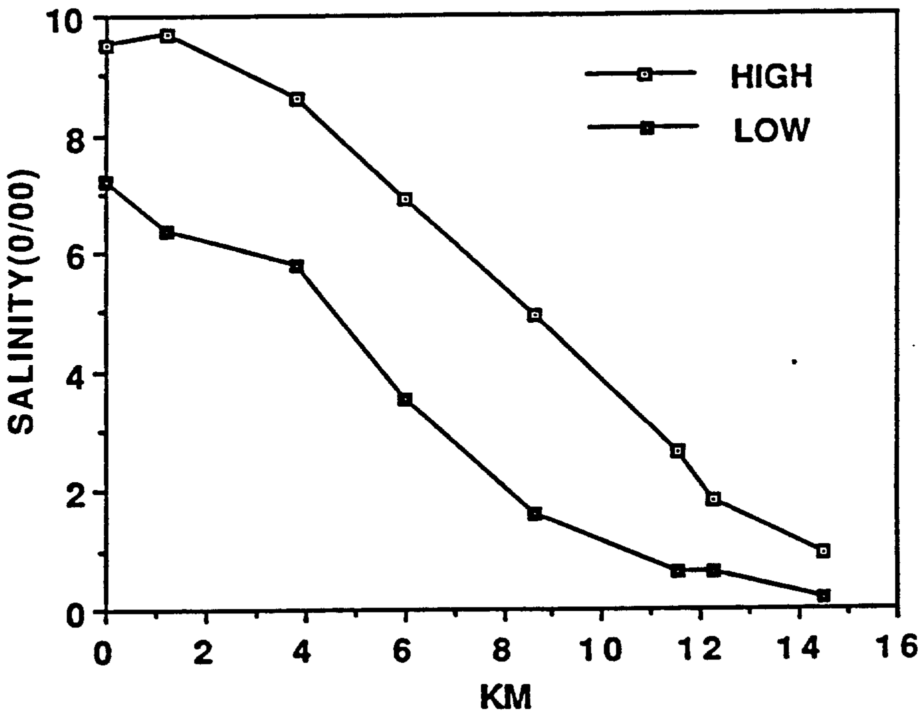

Figure 5. Salinity at sampling stations along the main channel of the Goose Creek estuary. Open squares indicate the overall means at high tide. Closed squares indicate overall means at low tide.

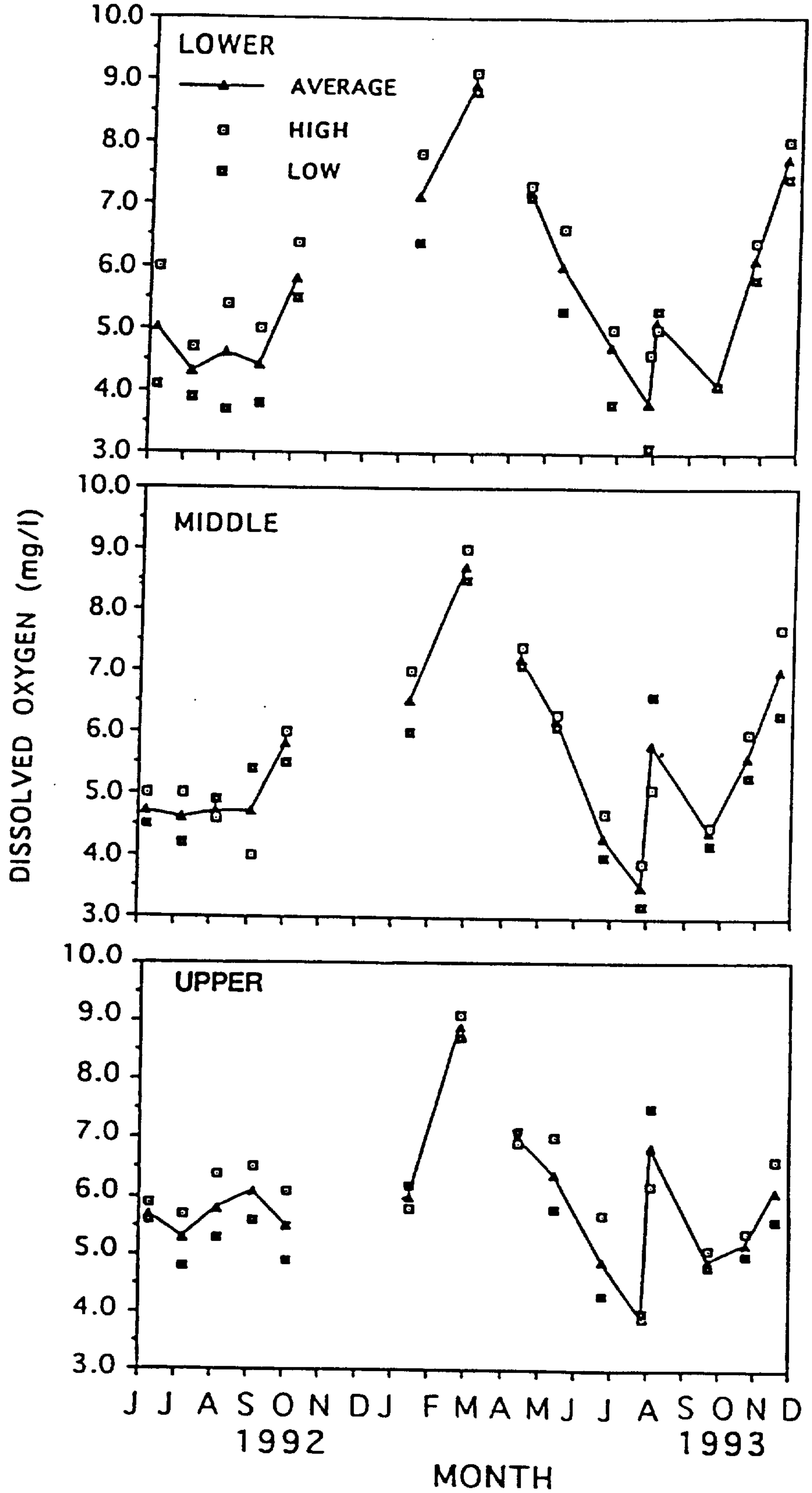

Figure 6. **Seasonal patterns of dissolved oxygen in the Goose Creek estuary by region.**

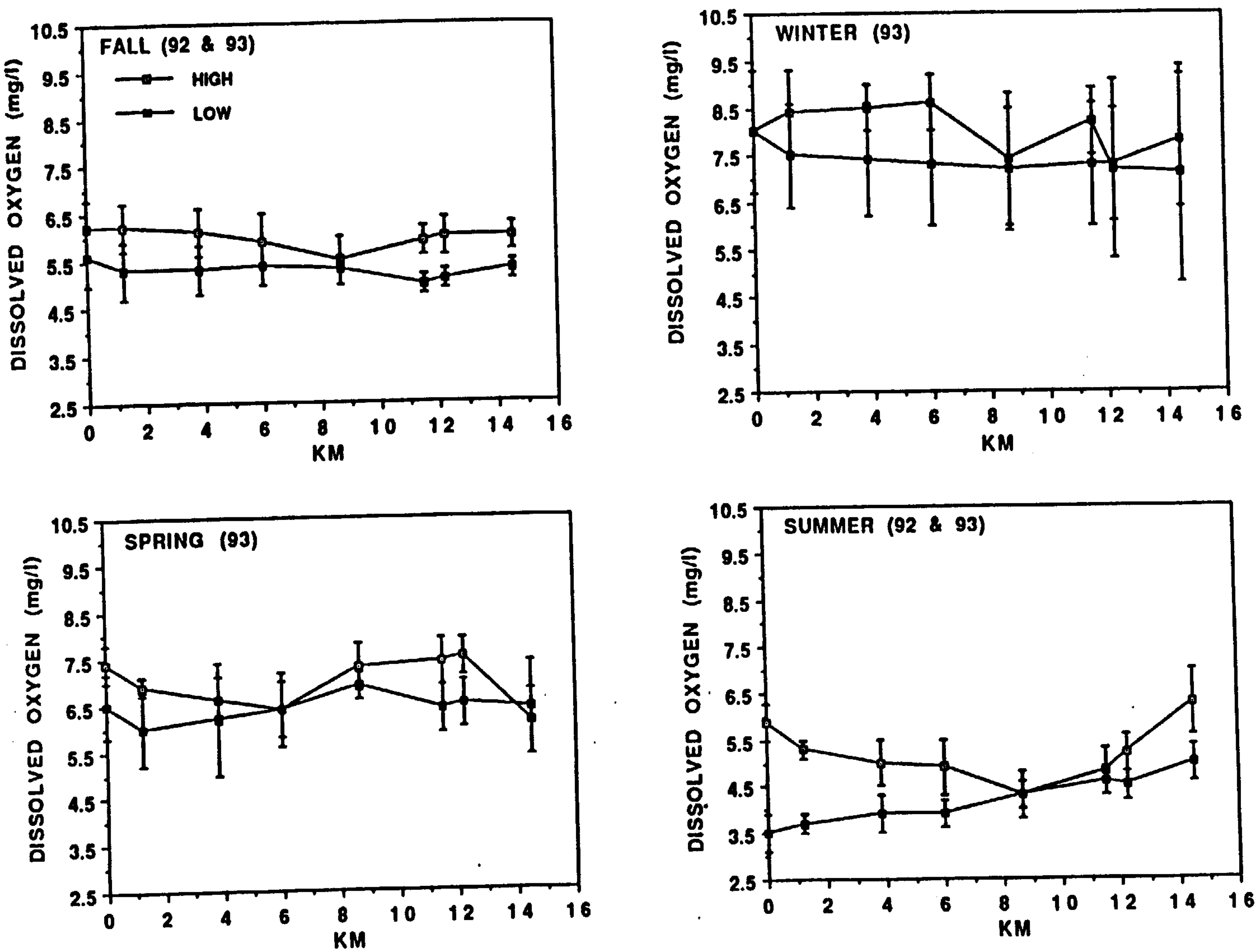

Figure 7. Spatial patterns of dissolved oxygen in the Goose Creek estuary by tide and season.

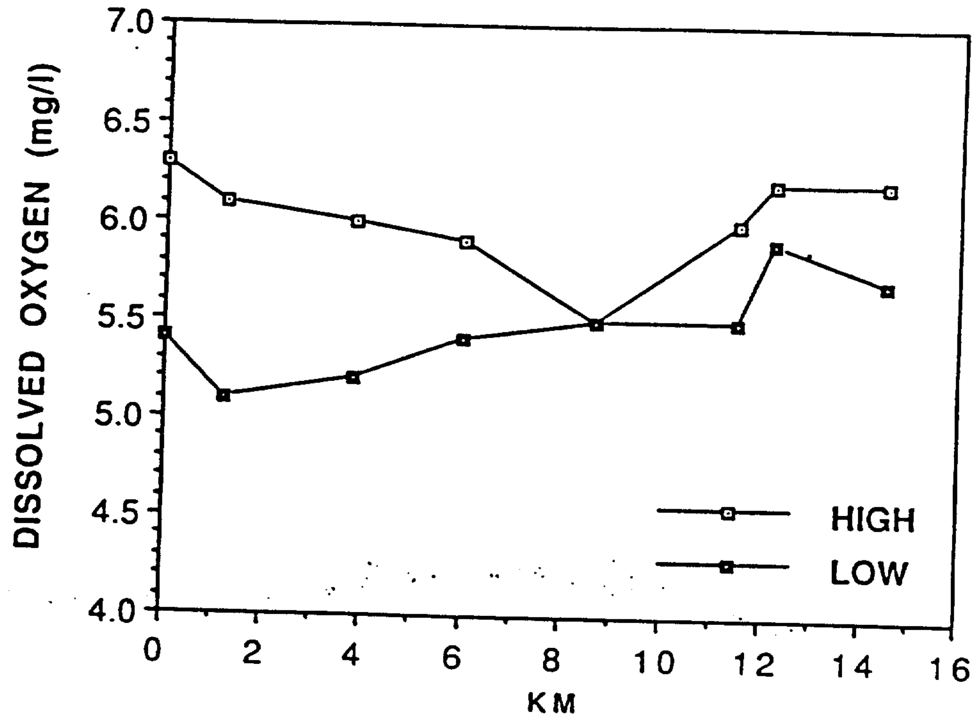

Figure 8. **Overall means for dissolved oxygen at sampling stations along the main channel of the Goose Creek estuary at high and low tides.**

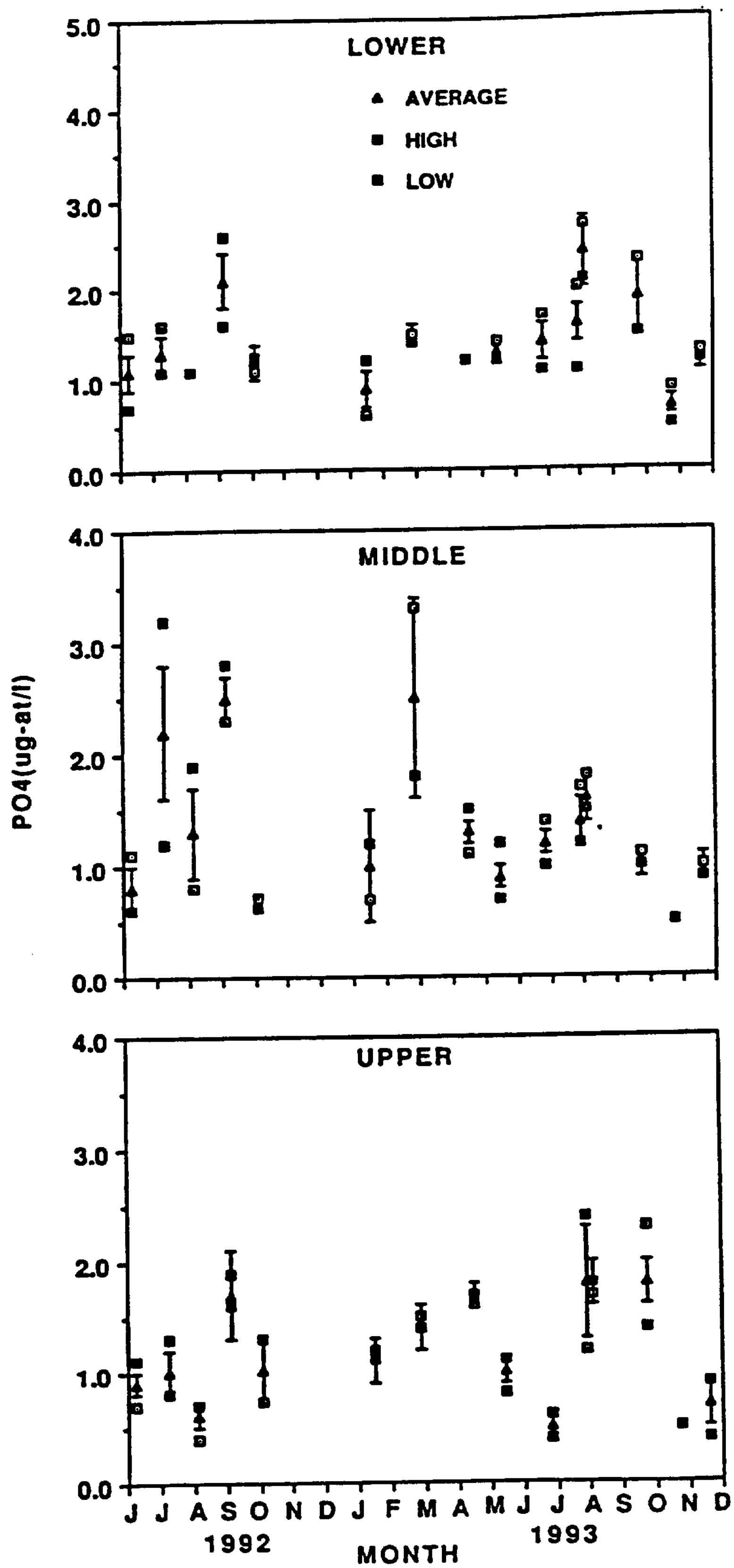

Figure 9. Seasonal patterns of orthophosphate in the Goose Creek estuary by region.

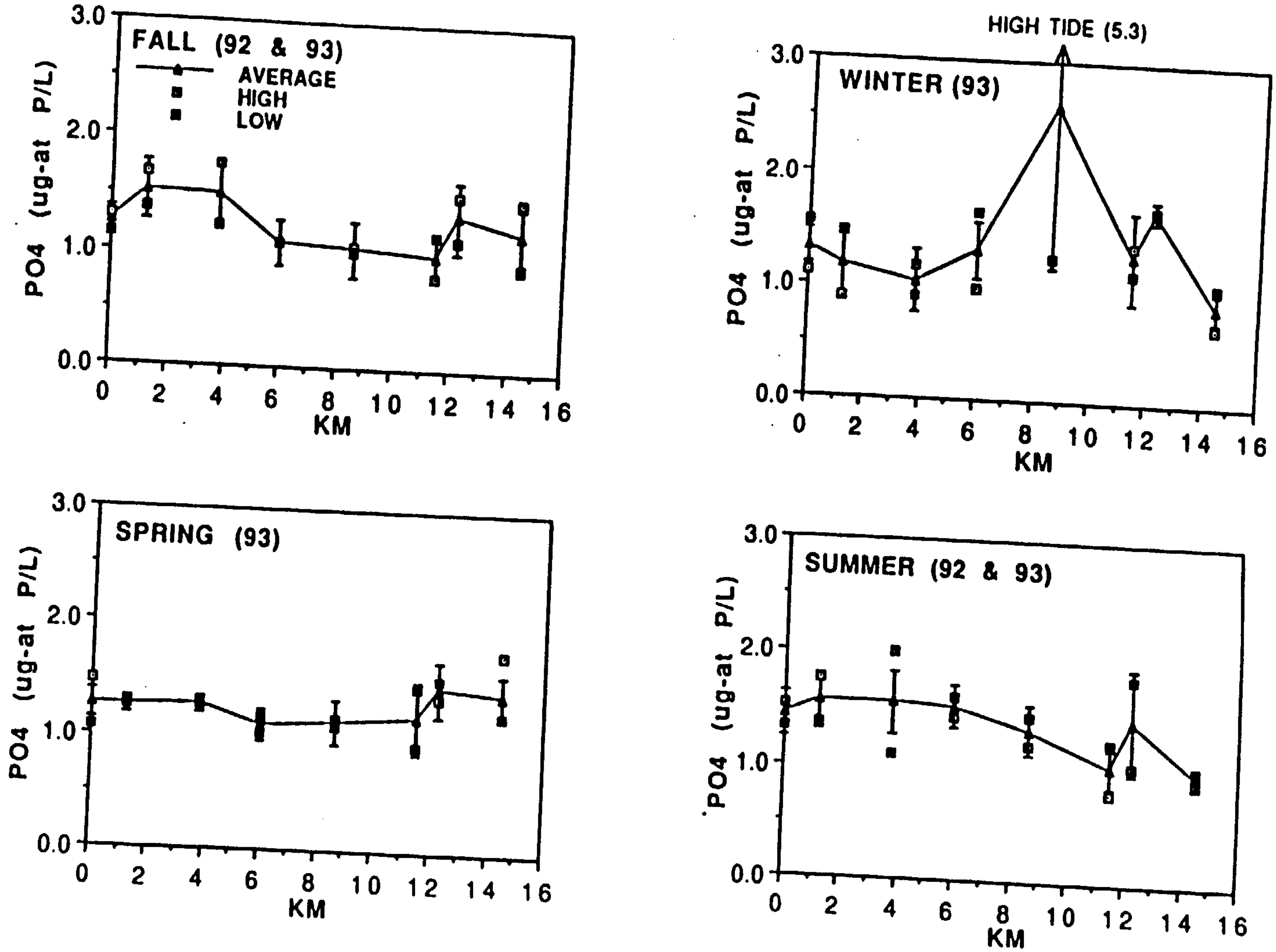

Figure 10. Spatial tidal patterns of orthophosphate in the Goose Creek estuary by season.

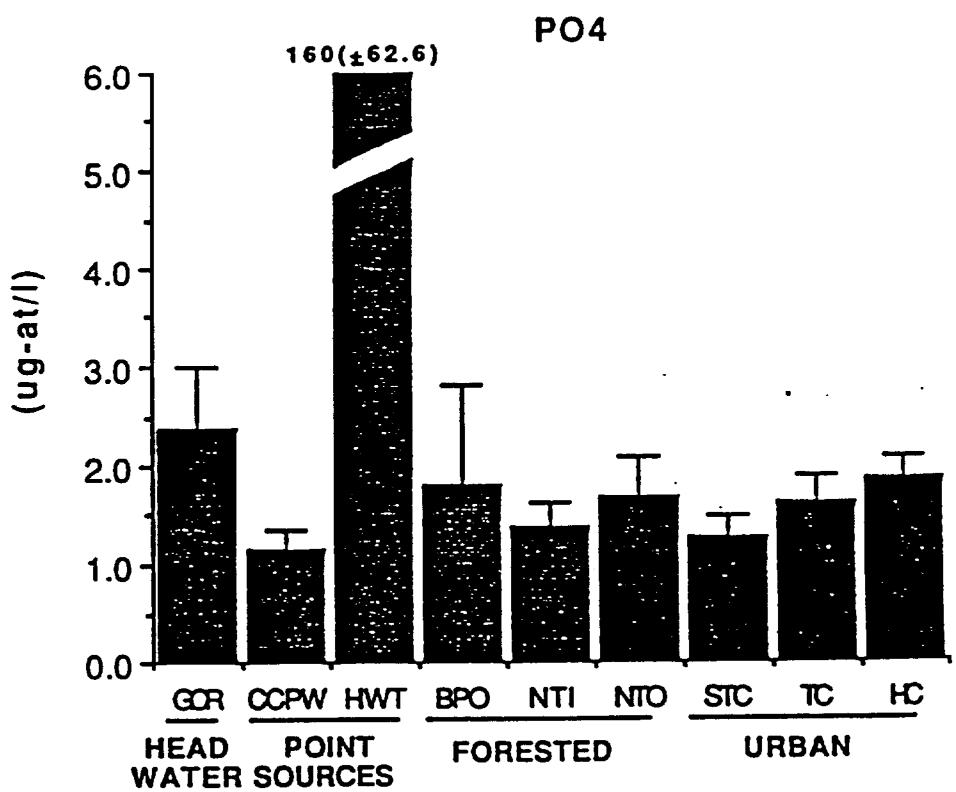

Figure 11. **Overall orthophosphate means (± SE) for the Goose Creek headwaters, point source discharges, and forested and urban tributaries in the Goose Creek estuary. GCR is the Goose Creek reservoir discharge into the headwaters of the Goose Creek estuary. CCPW is the Charleston Commissioners of Public Works, a drinking water processing facility. HWT is the Hanahan Wastewater Treatment facility. BPO is the Brown Pond outflow, NTI is New Tenant Pond inflow and NTO is the New Tenant Pond outflow. HC is Hanahan Creek and TC is Turkey Creek which are tidal creeks in an urbanized watershed; STC is South Turkey Creek which is a non tidal reach upstream on the Turkey Creek tributary.**

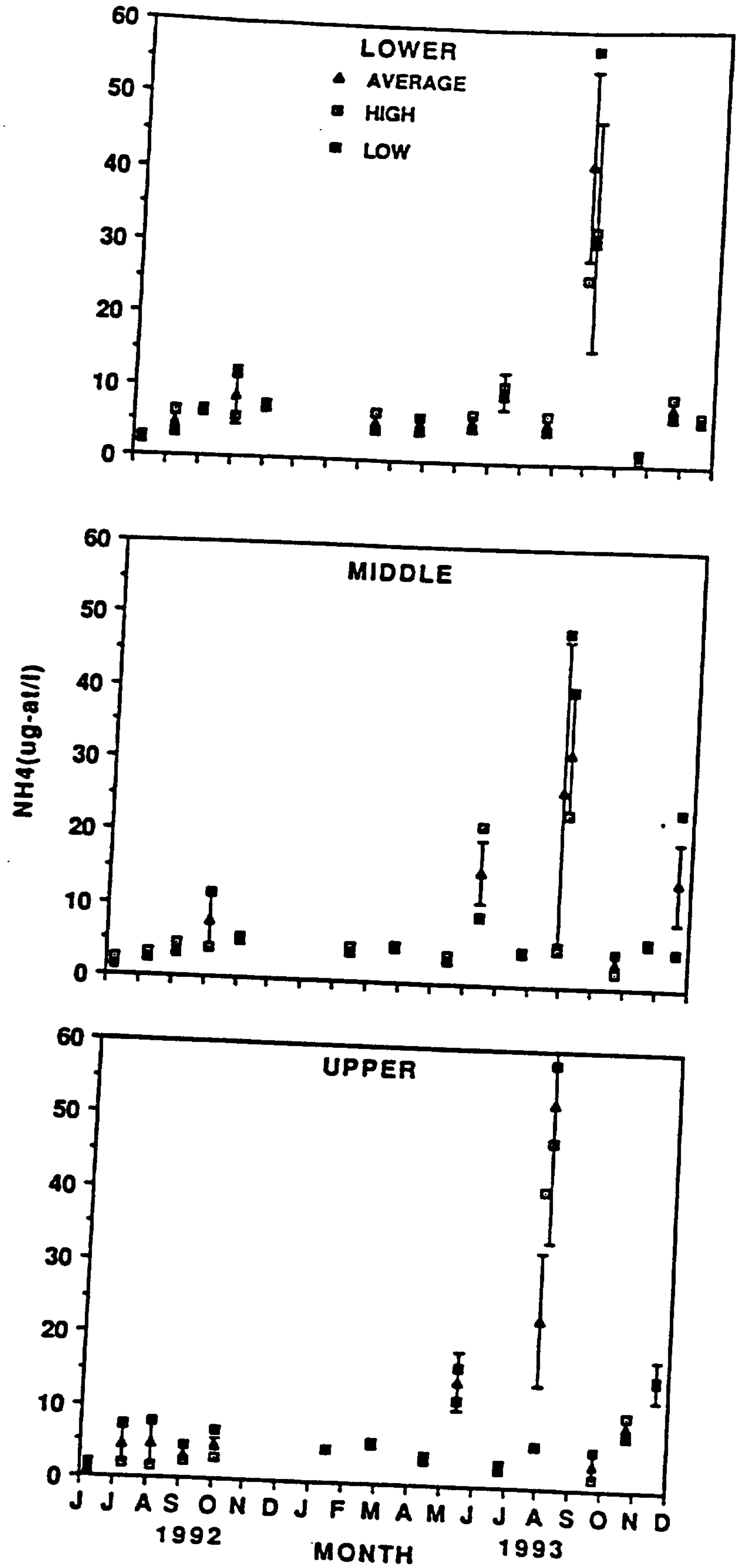

Figure 12. Seasonal patterns of ammonium in the Goose Creek estuary by region.

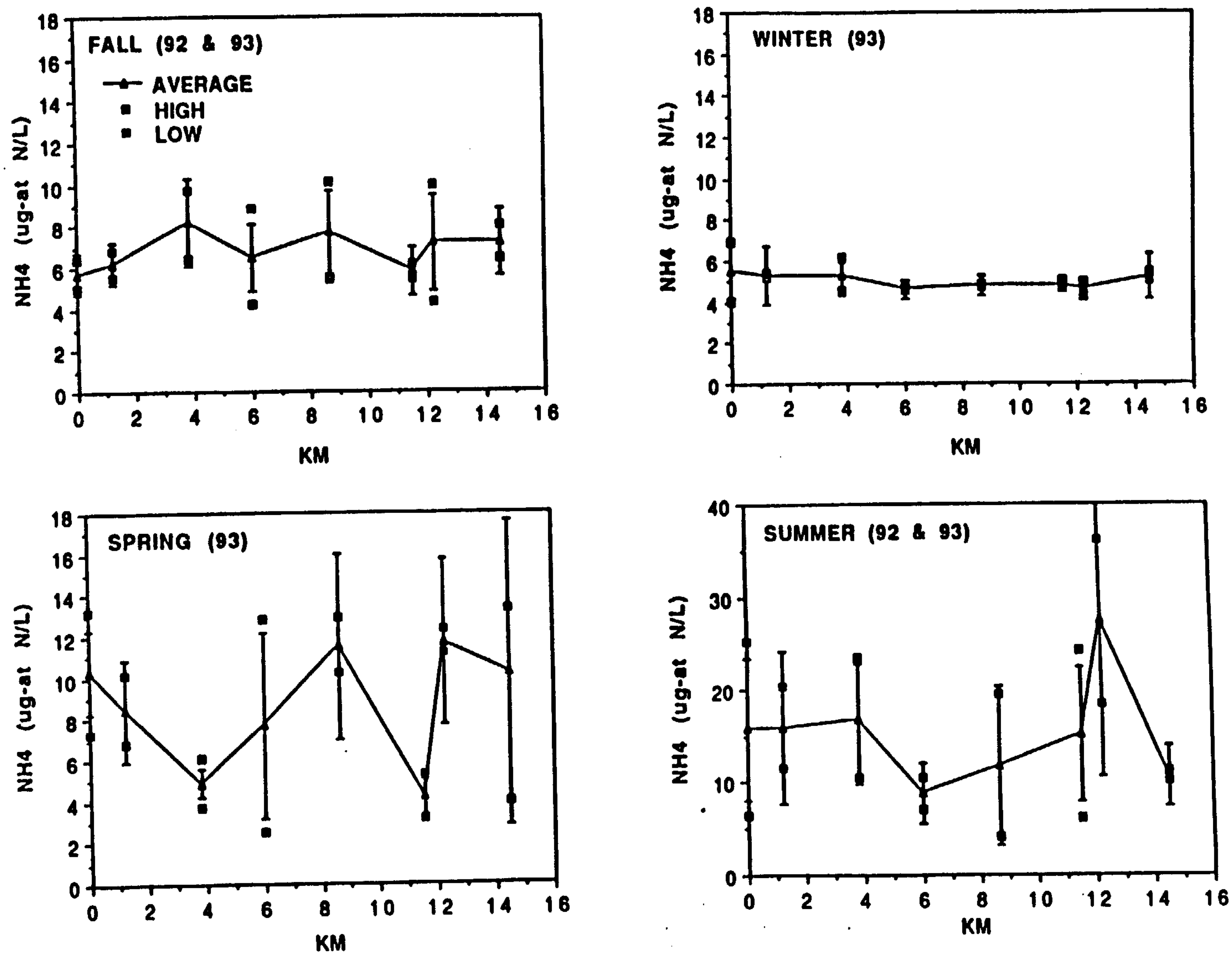

Figure 13. **Spatial tidal patterns of ammonium in the Goose Creek estuary by season.**

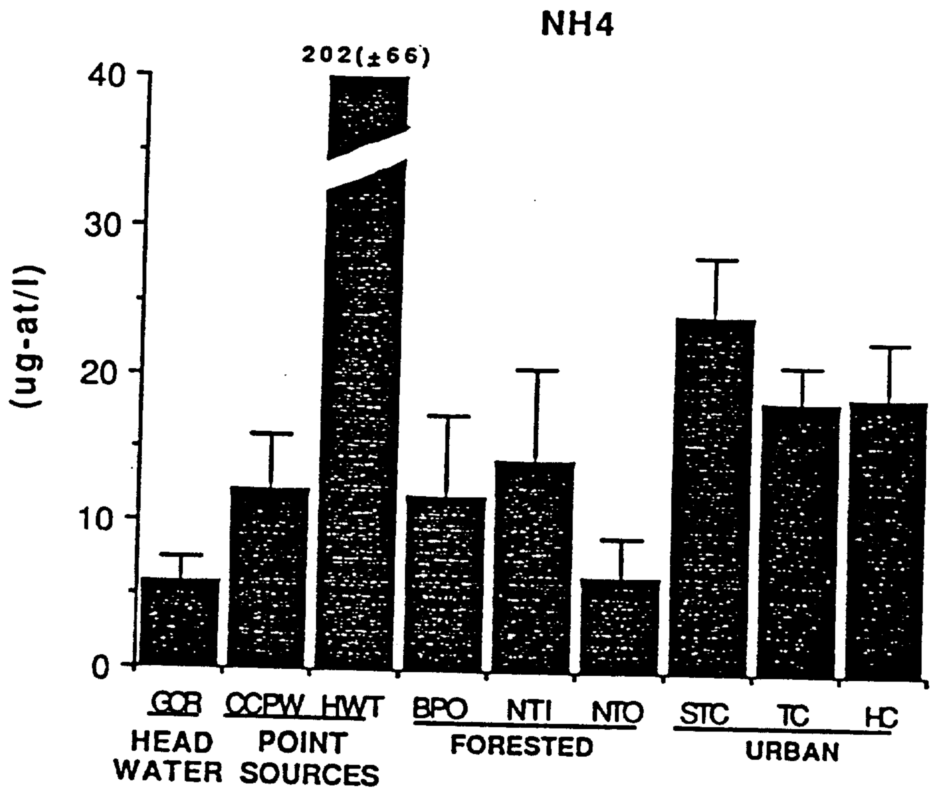

Figure 14. **Overall ammonium means (± SE) for the Goose Creek headwaters, point source discharges, and forested and urban tributaries in the Goose Creek estuary.**

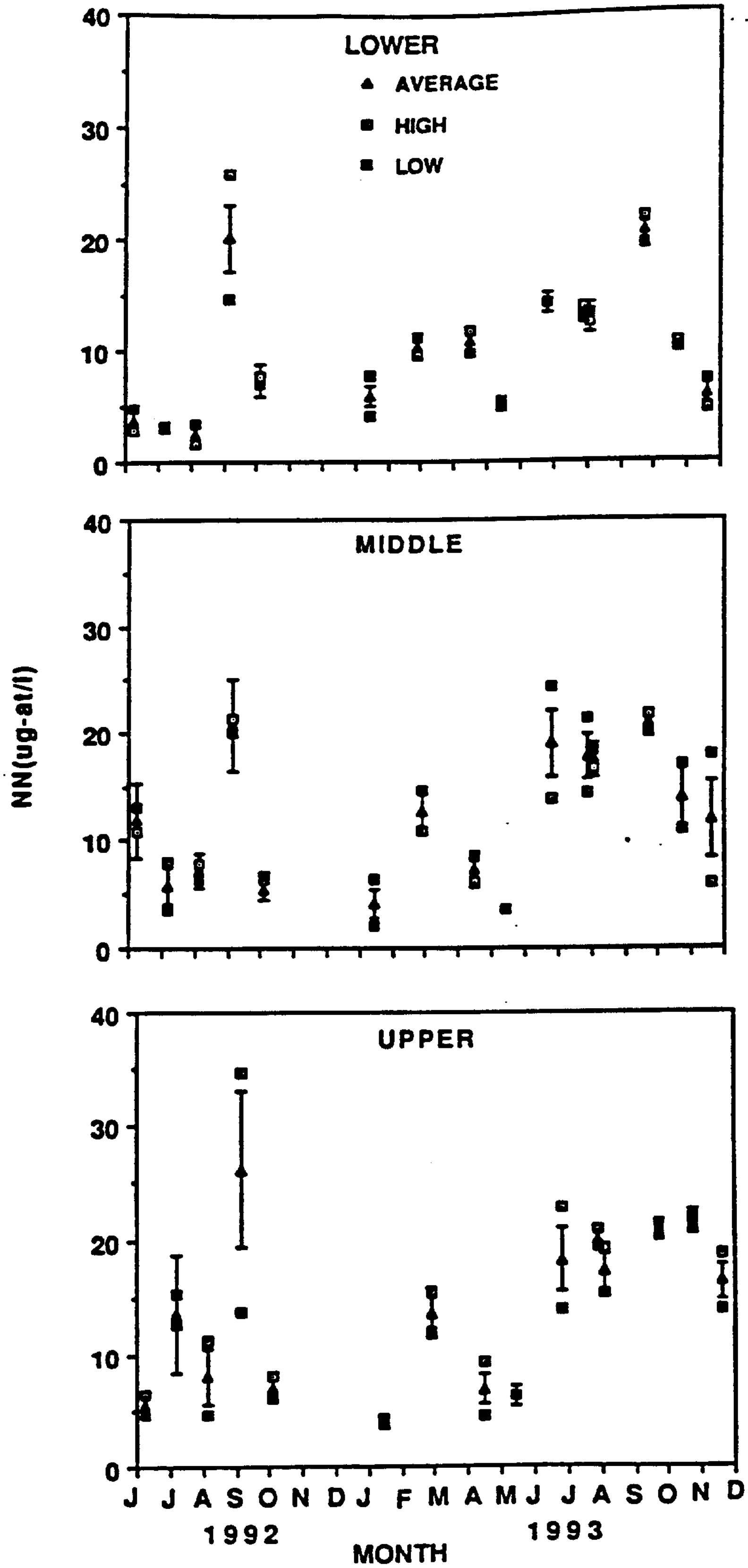

Figure 15. Seasonal patterns of nitrate in the Goose Creek estuary by region.

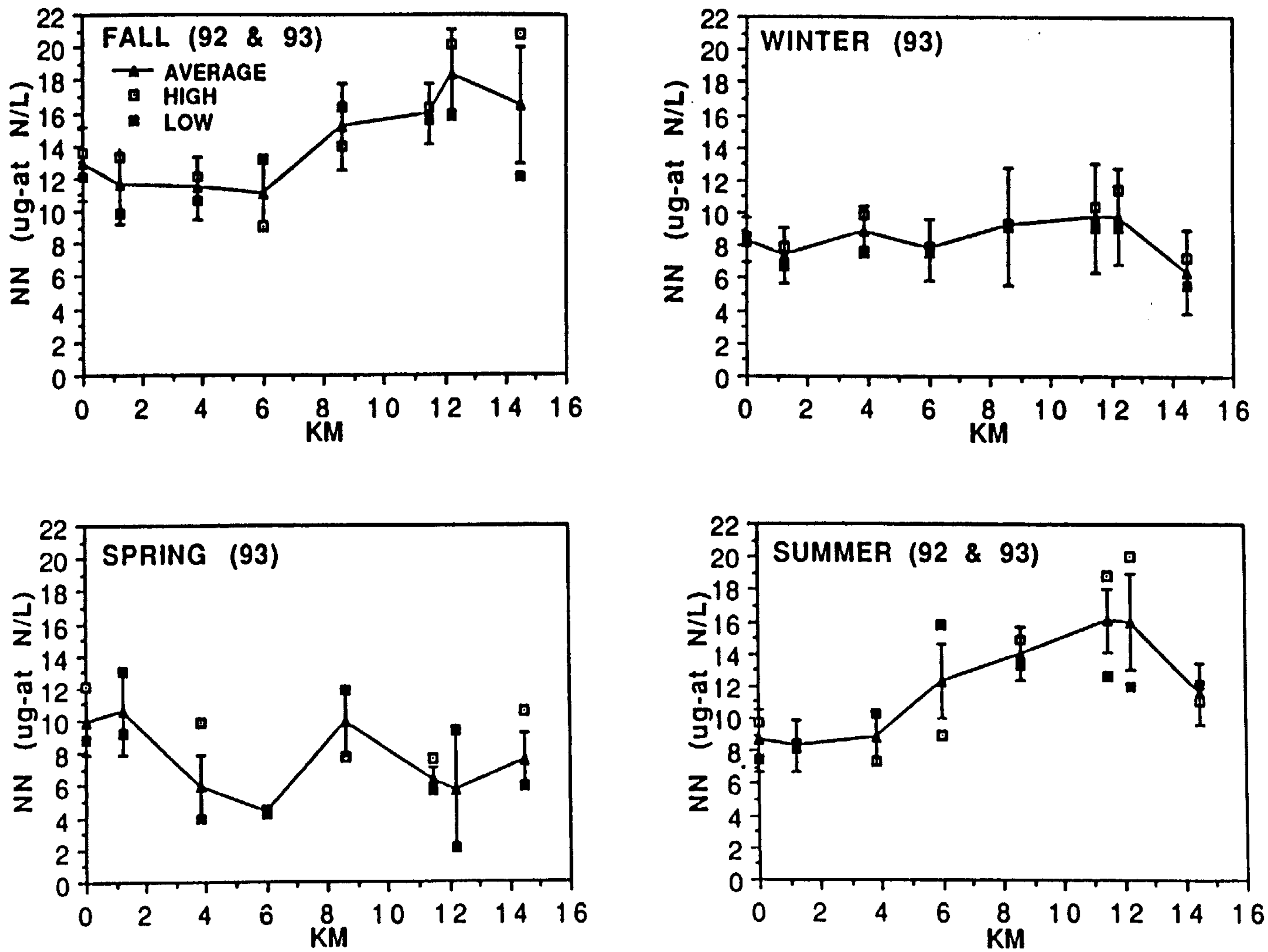

Figure 16. **Spatial tidal patterns of nitrate in the Goose Creek estuary by season.**

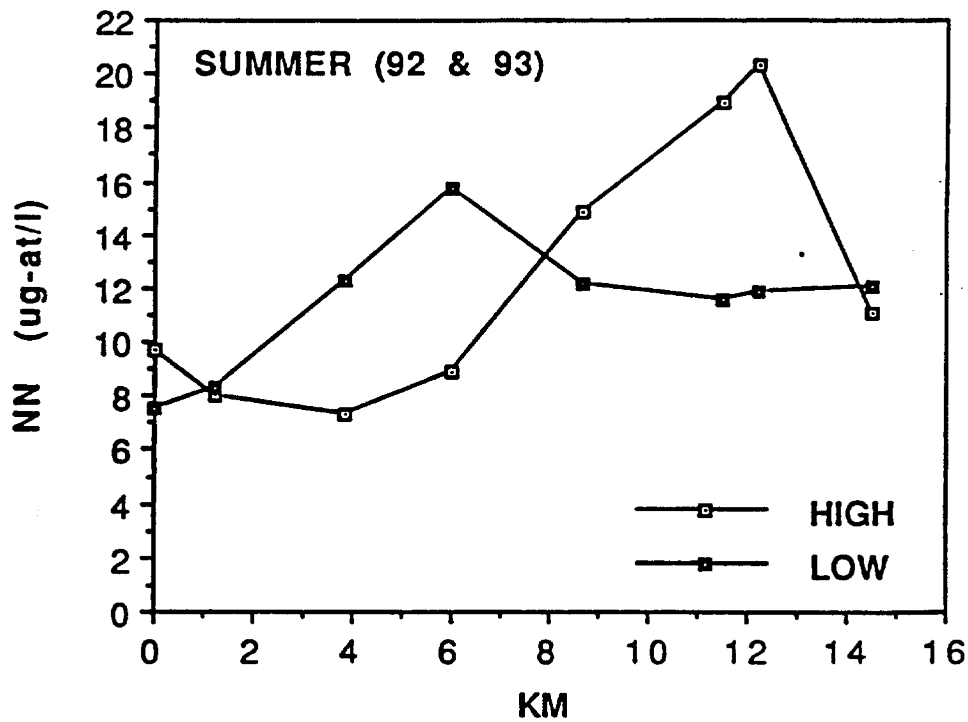

Figure 17. **Spatial tidal patterns of nitrate in the Goose Creek estuary during the summer (1992 & 1993).**

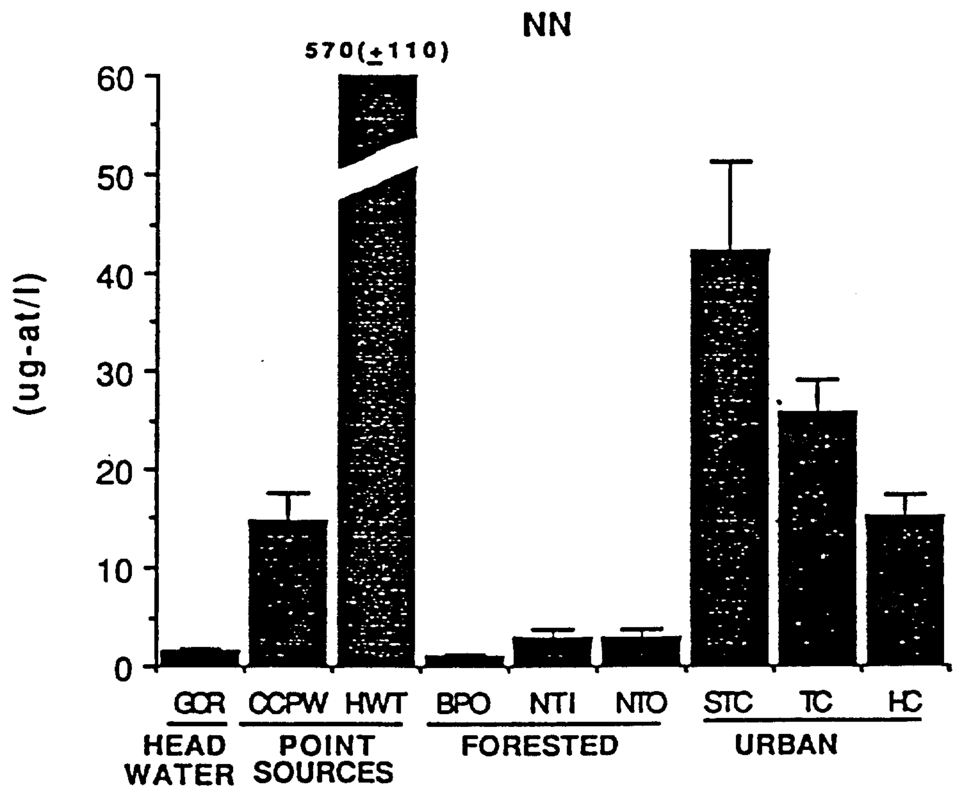

Figure 18. **Overall nitrate means (± SE) for the Goose Creek headwaters, point source discharges, and forested and urban tributaries in the Goose Creek estuary.**

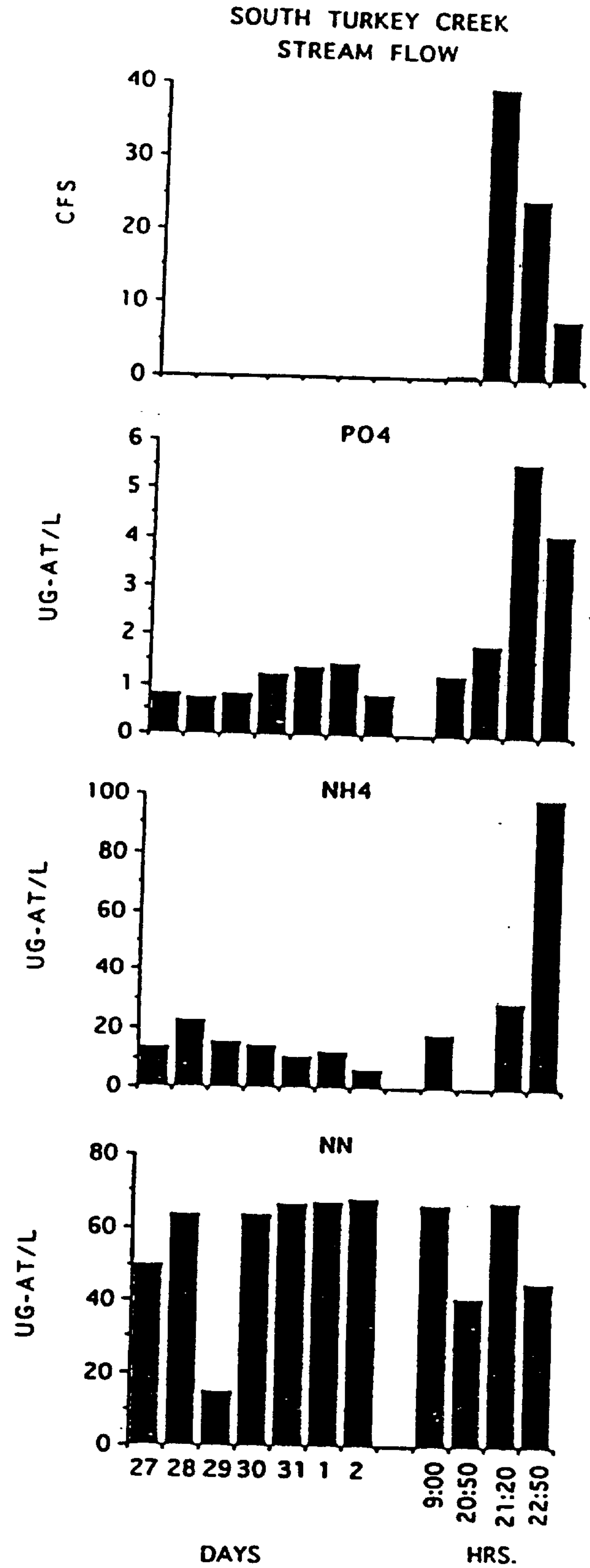

Figure 19. **Streamflows and orthophosphate, ammonium, and nitrate concentrations in South Turkey Creek as a function of time proceeding and during a storm event from July 27 to August 3, 1993.**

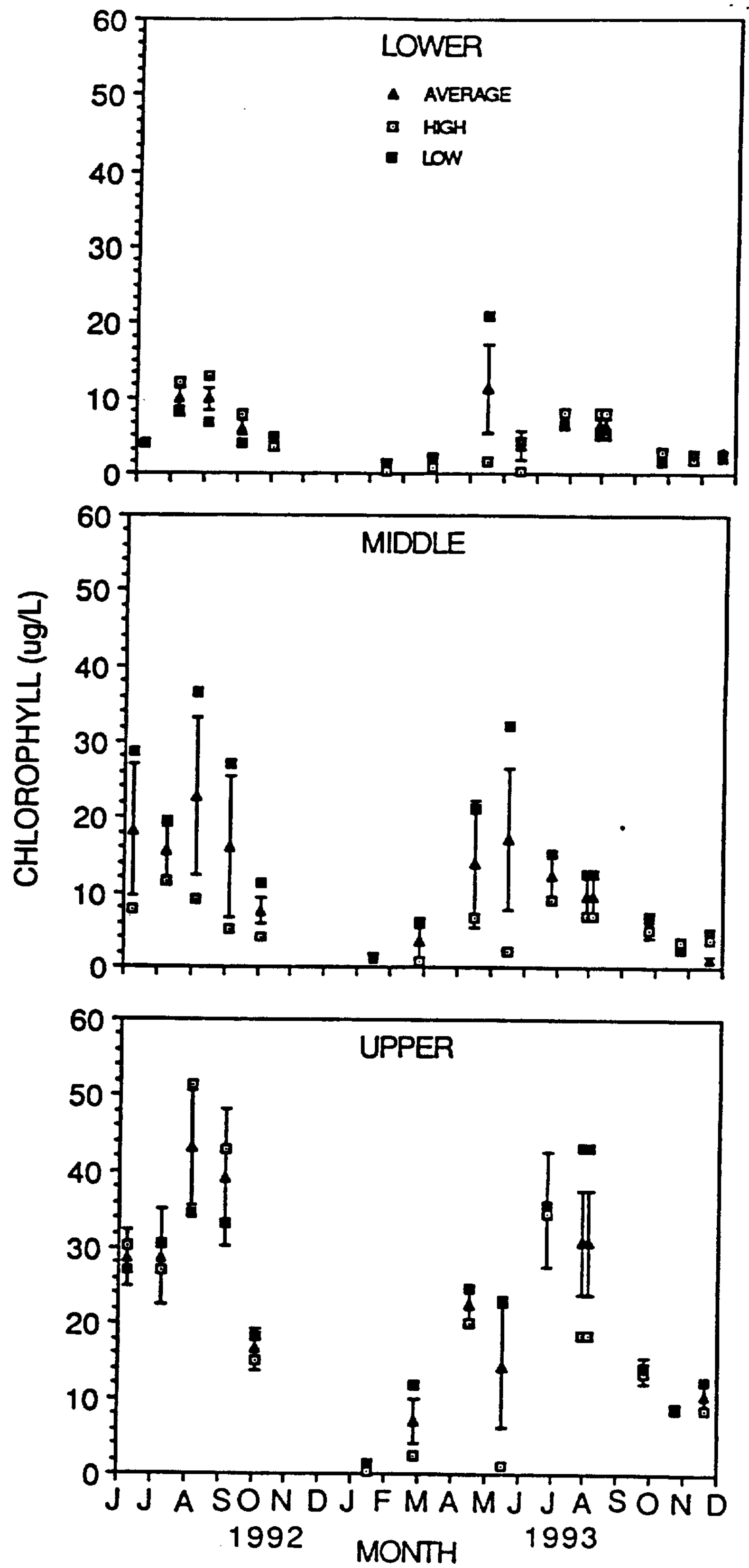

Figure 20. Seasonal patterns of chlorophyll in the Goose Creek estuary by region.

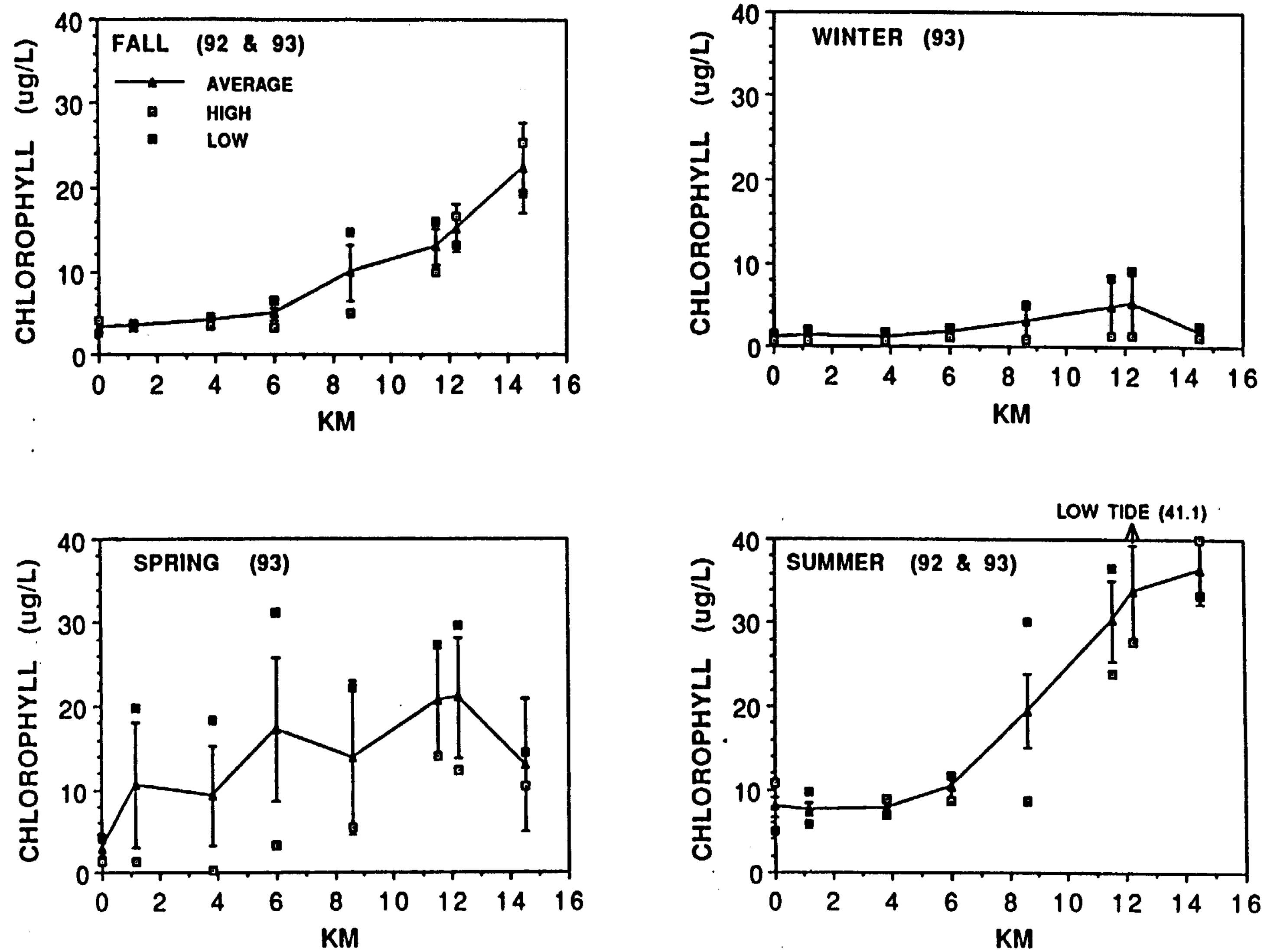

Figure 21. Spatial tidal patterns of chlorophyll in the Goose Creek estuary by season.

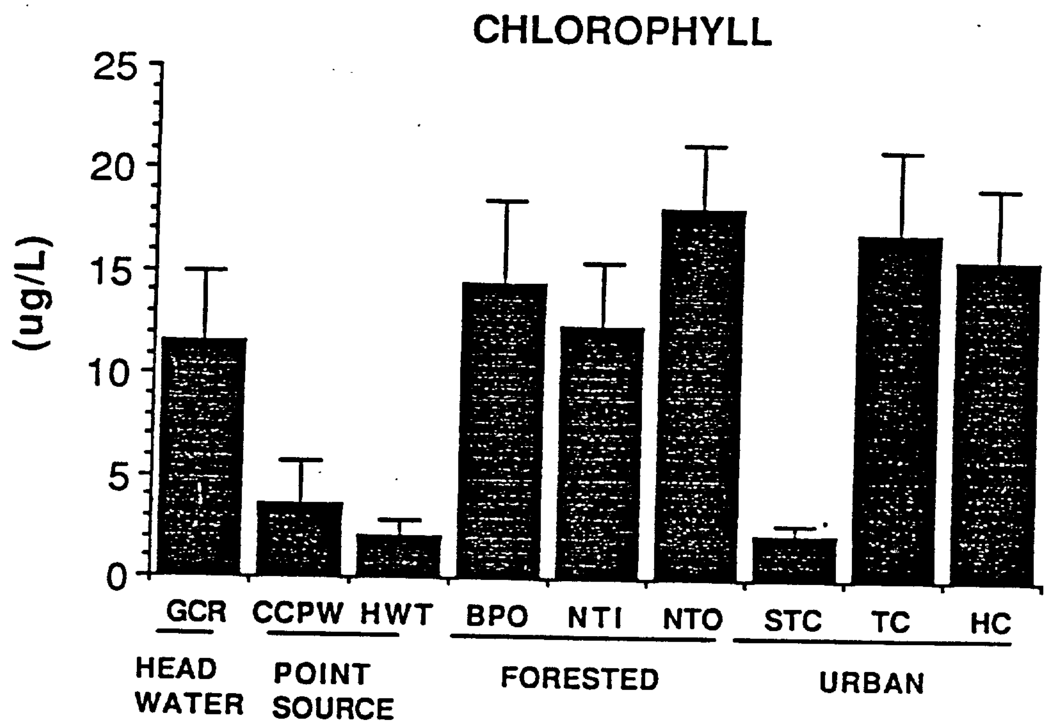

Figure 22. **Overall chlorophyll means (± SE) for the Goose Creek headwaters, point source discharges, and forested and urban tributaries in the Goose Creek estuary.**

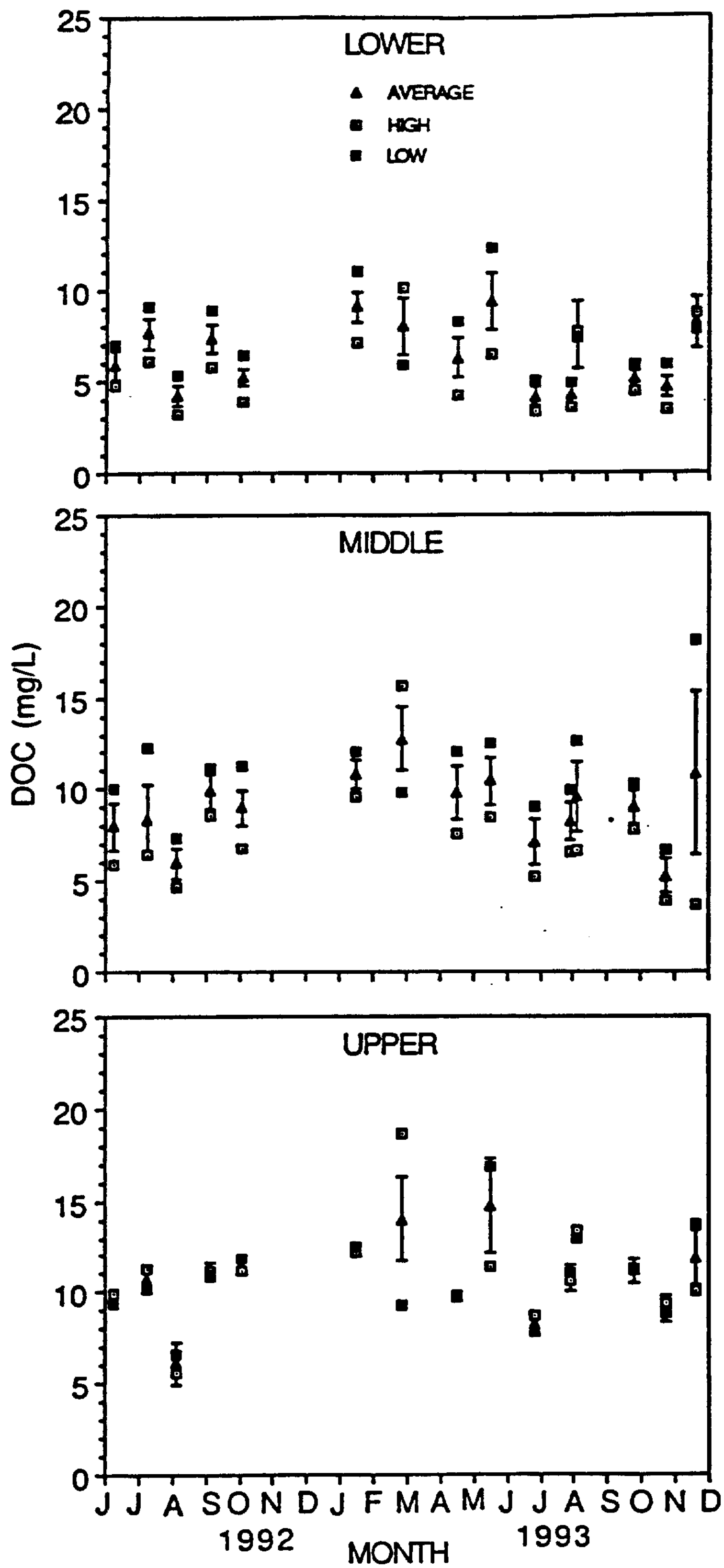

Figure 23. **Seasonal patterns of dissolved organic carbon in the Goose Creek estuary by region.**

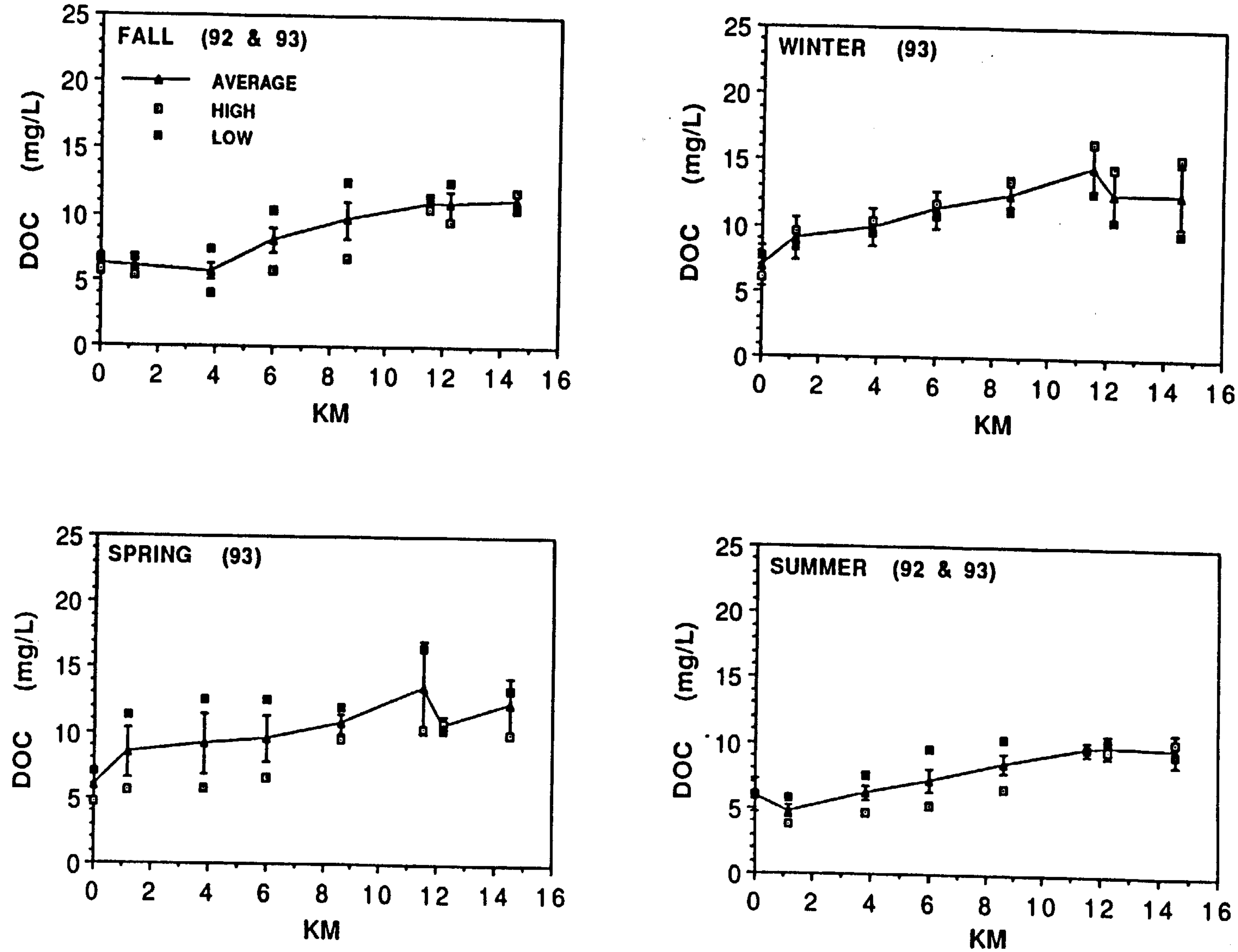

Figure 24. Spatial tidal patterns of dissolved organic carbon in the Goose Creek estuary by season.

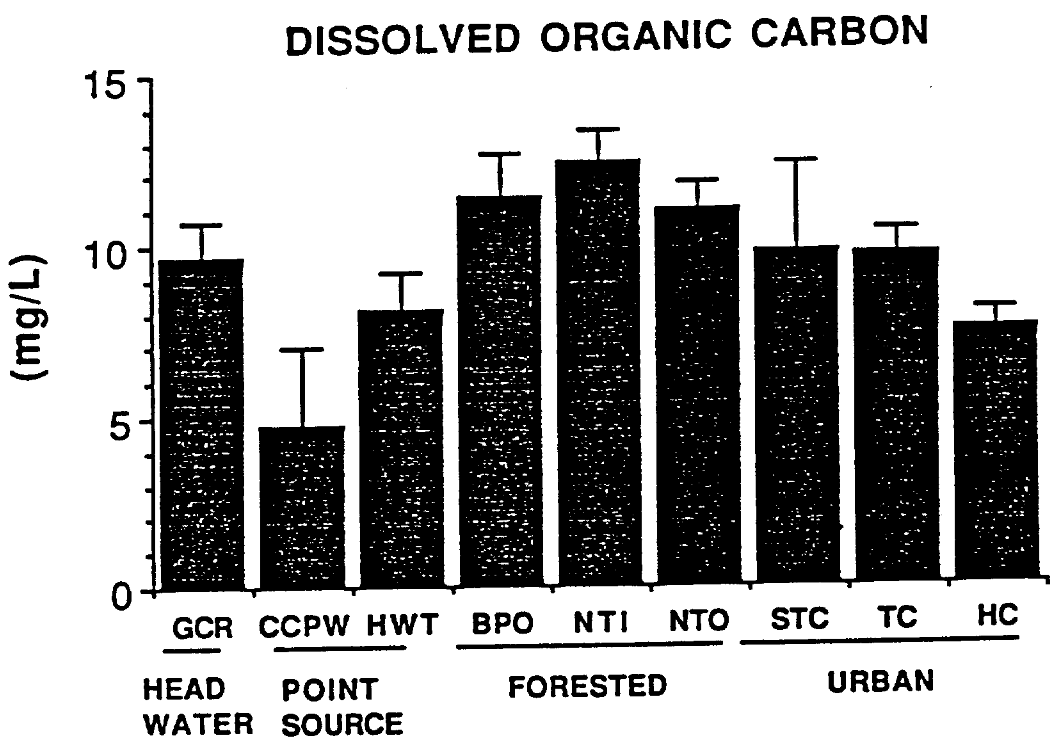

Figure 25. Overall dissolved organic carbon means (± SE) for the Goose Creek headwaters, point source discharges, and forested and urban tributaries in the Goose Creek estuary.

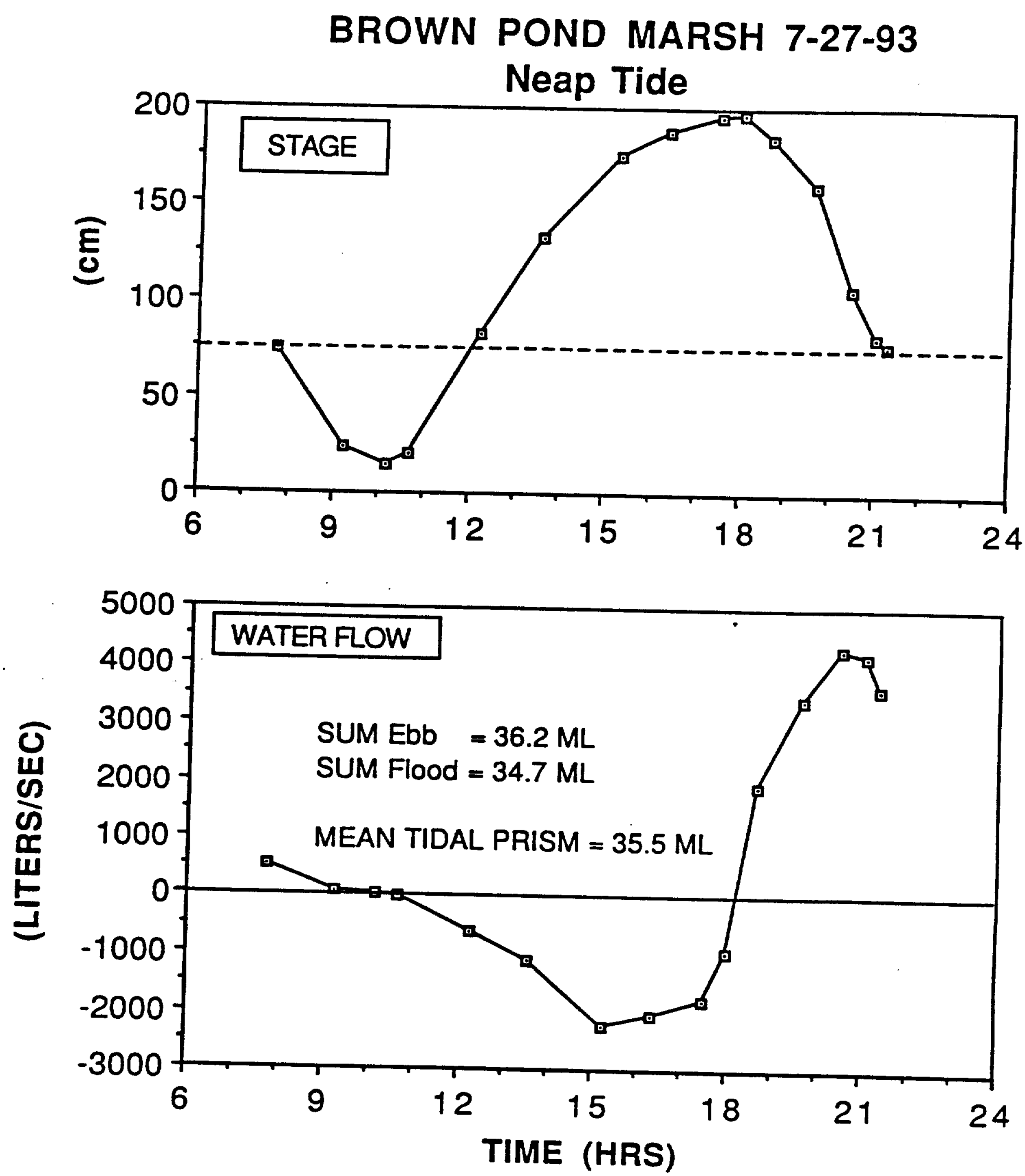

Figure 26. **Tide stage and water flow for Browns Marsh. (7/27/93)**

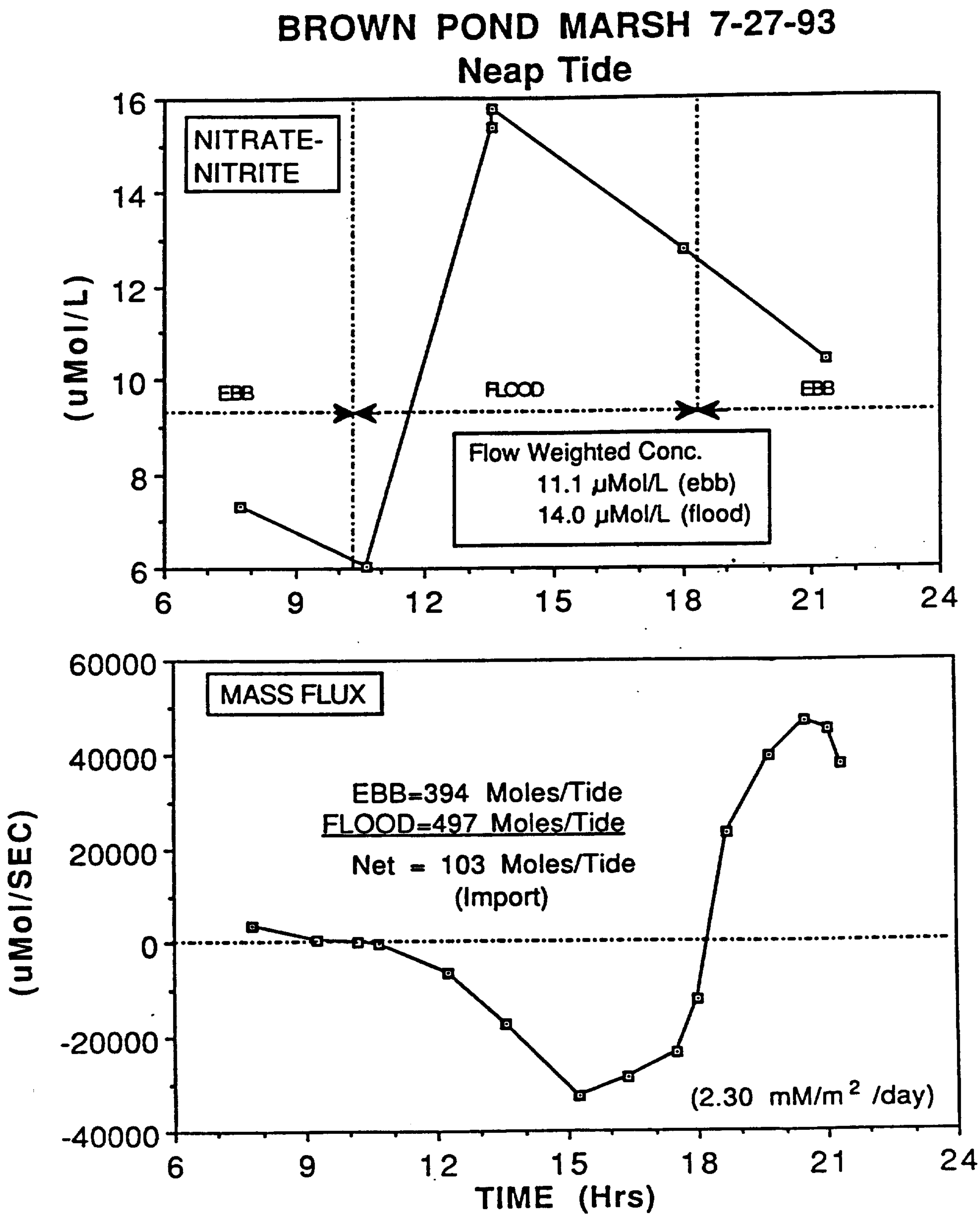

Figure 27. **Nitrate-nitrite concentrations and mass flux for Browns Marsh. (7/27/93)**

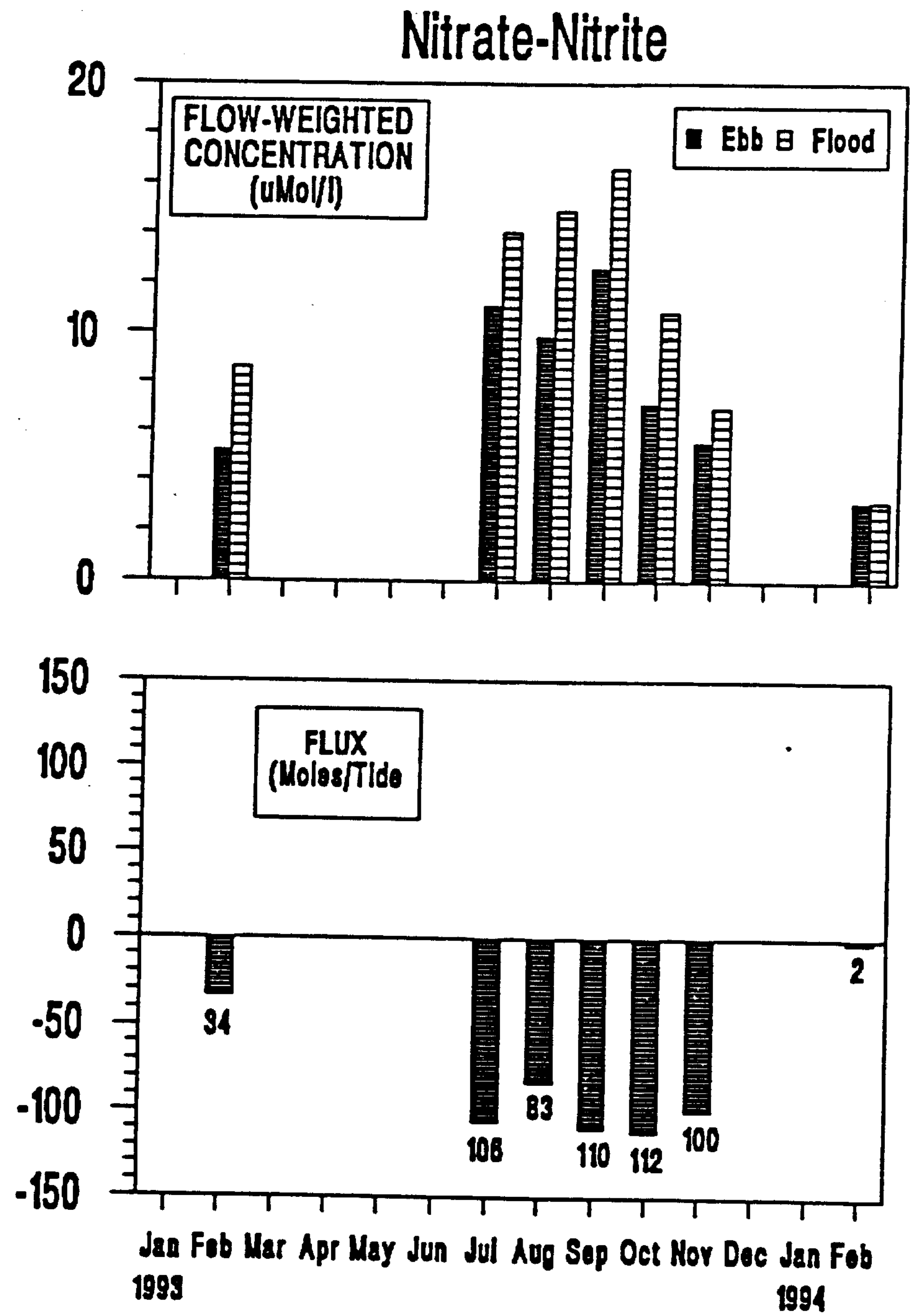

Figure 28. Flow-weighted concentrations and net tidal exchange on nitrate-nitrite between Browns Marsh and the Goose Creek estuary

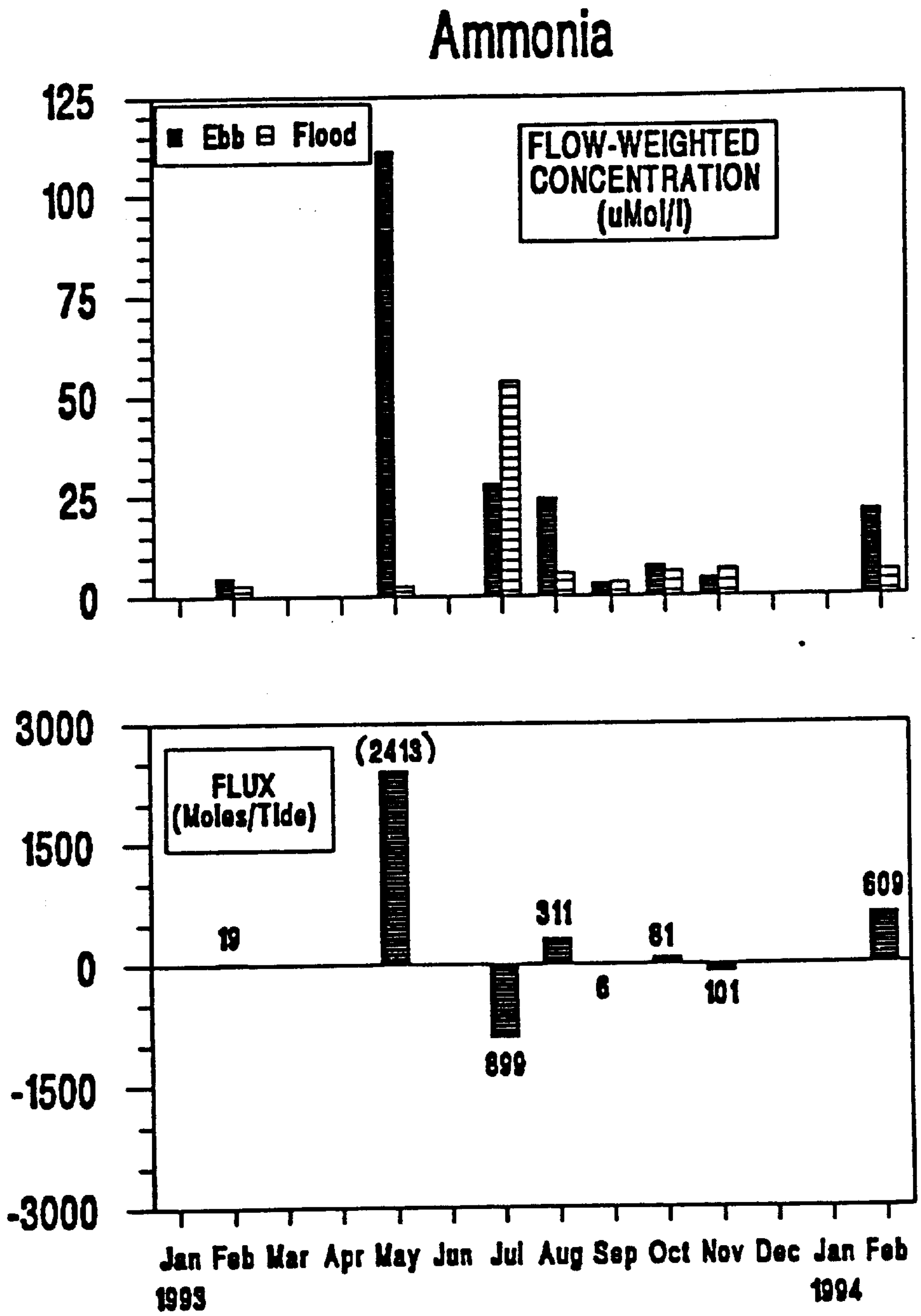

Figure 29. Flow-weighted concentrations and net tidal exchange of ammonium between Browns Marsh and the Goose Creek estuary.

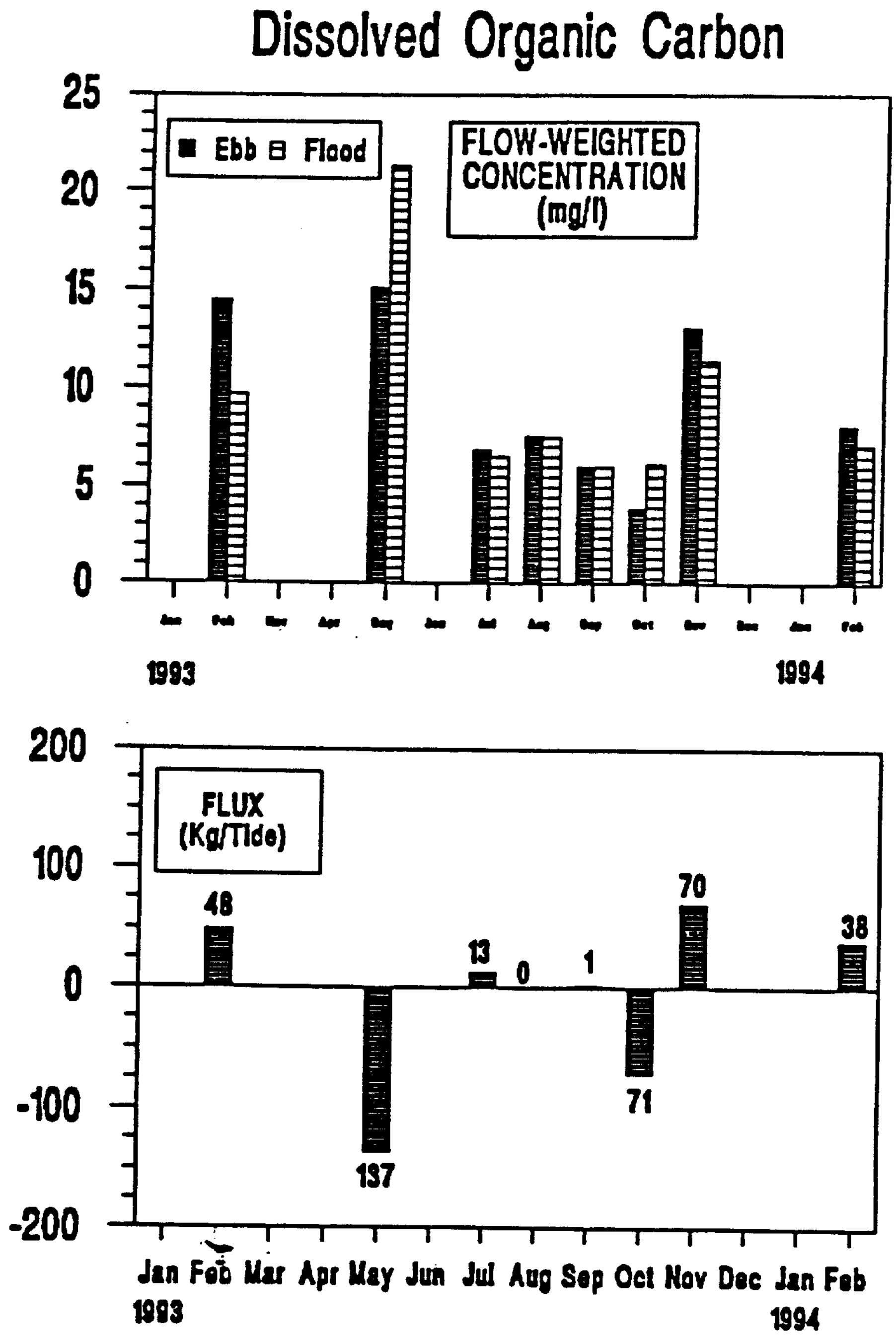

Figure 30. **Flow-weighted concentrations and net tidal exchange of dissolved organic carbon between Browns Marsh and the Goose Creek estuary.**

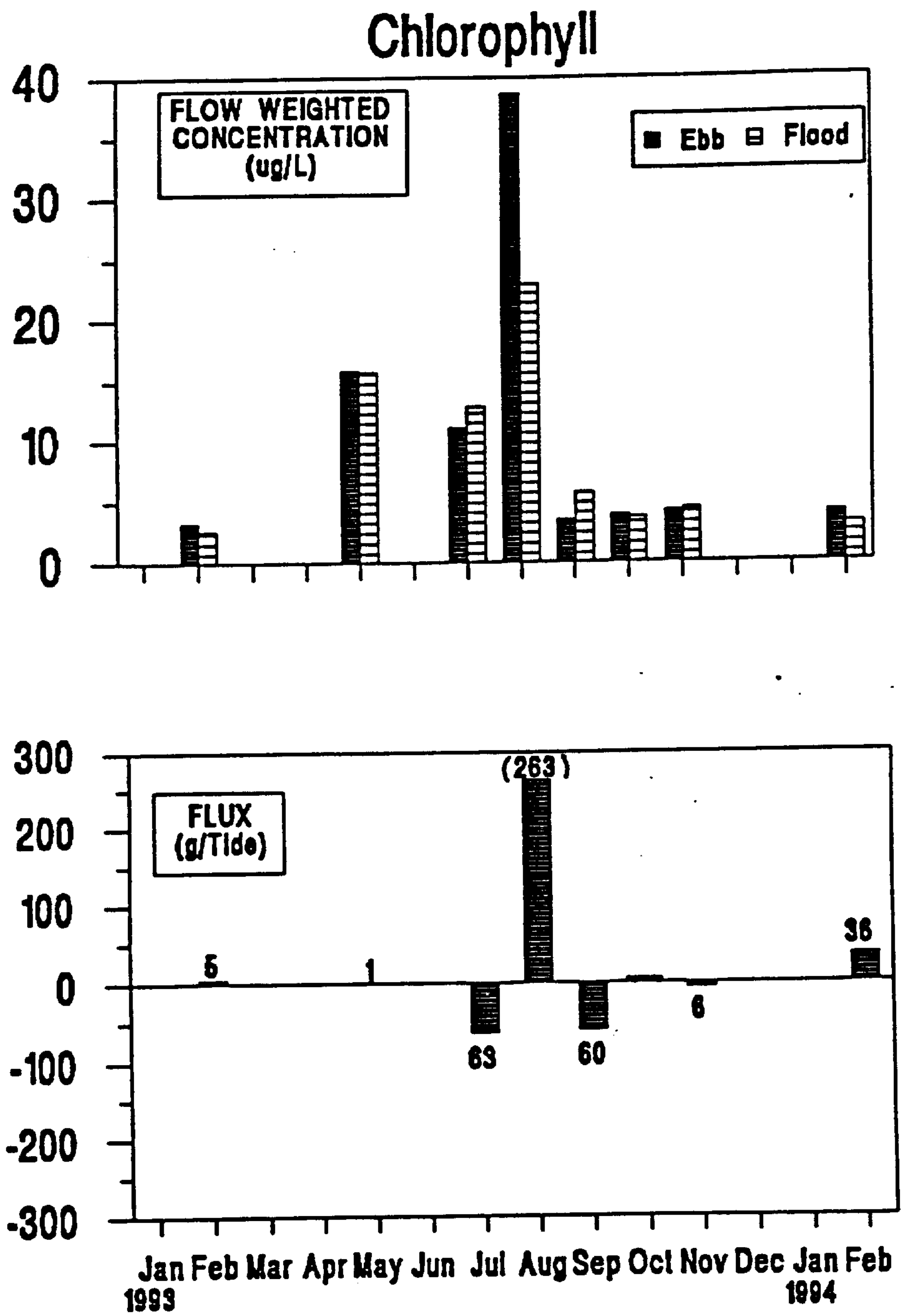

Figure 31. **Flow-weighted concentrations and net tidal exchange of chlorophyll-a between Browns Marsh and the Goose Creek estuary.**

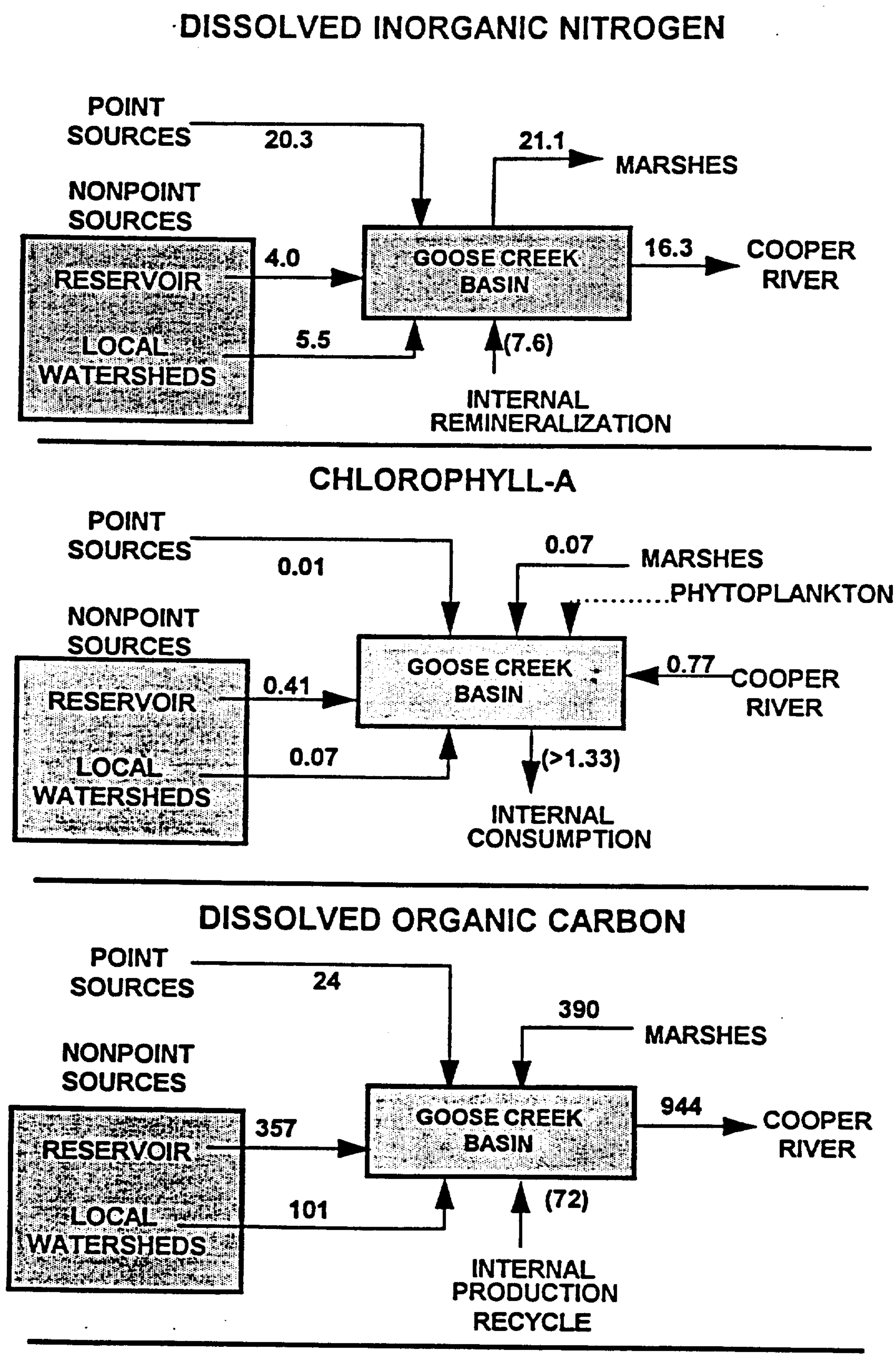

Figure 32. **Mass balances for Goose Creek sub-basin (metric tonnes/yr)**

Table 1. Land Use Distributions in the Goose Creek Watershed and Sub-basins (Data from Blood and Darbar, personal communications). "Total Watershed" includes drainage basin for the Goose Creek Reservoir; "Lower Watershed" includes only the drainage areas below the Goose Creek Reservoir; "Forested" land cover includes upland evergreen, mixed deciduous, shrub/scrub and forested wetlands; "Urban" includes commercial, industrial, residential, highways, airport, and other disturbed and built-up land.

	Toal Area (km^2)	%Forest	%Urban	%Agr	%Marsh	%Water
Total Watershed	143.1	47.0	42.9	2.0	5.0	3.2
Lower Watershed	46.5	38.2	39.3	2.6	14.9	5.0
Urban Sub-Basins						
Turkey Creek (Upper)	5.4	11.9	*86.3	0.9	0.7	0.2
Turkey Creek (Lower)	4.4	11.3	**86.6	1.0	1.1	0.0
Hanahan Creek	3.9	2.5	**96.9	0.3	0.2	0.1
Forested Sub-Basins						
New Tenant (Upper)	4.6	77.9	***14.0	1.9	5.8	0.4
New Tenant (Lower)	.7	76.2	***7.2	0.7	5.0	10.9
Brown Pond	2.3	56.2	***38.1	1.6	2.3	1.8
Logan Pond	1.5	69.5	***28.6	1.0	0.8	0.1

* Dominated by commercial development and airport

** Dominated by single family residential

*** Military installations

Table 2. **Overall and Seasonal Means (± SE) for Physical Parameters, Nutrients, Organic Matter and Algal Biomass in the Goose Creek Estuary (Main Channel)**

	OVERALL	FALL	WINTER	SPRING	SUMMER
PHYSICAL PARAMETERS					
Temperature (° C)	22.2*	22.7 ± 0.4	10.9 ± 0.3	22.1 ± 0.6	29.2 ± 0.1
Salinity (ppt)	4.6 ± 0.3	5.4 ± 0.4	1.3 ± 0.3	3.9 ± 0.6	5.0 ± 0.5
Dissolved Oxygen (mg/l)	5.8 ± 0.1	5.6 ± 0.1	7.7 ± 0.2	6.7 ± 0.1	4.9 ± 0.1
NUTRIENTS					
Orthophosphate (µg-at/l)	1.3 ± 0.1	1.2 ± 0.1	1.4 ± 0.2	1.3 ± 0.1	1.3 ± 1.3
Ammonium (µg-at/l)	9.7 ± 1.0	6.8 ± 0.6	5.1 ± 0.3	8.6 ± 1.3	14.8 ± 2.7
Nitrate (µg-at/l)	11.9 ± 0.5	14.0 ± 0.9	8.5 ± 0.8	7.5 ± 0.7	11.8 ± 0.7
ORGANIC MATTER/ ALGAL BIOMASS					
DOC (mg/l)	8.7 ± 0.2	8.5 ± 0.4	11.1 ± 0.7	9.9 ± 0.7	7.7 ± 0.3
POC (mg/l)	2.8 ± 0.3	2.2 ± 0.3	7.4 ± 1.0	0.9 ± 0.3	2.3 ± 0.3
Chlorophyll-a (µg/l)	12.4 ± 0.9	9.3 ± 1.1	2.5 ± 0.7	13.5 ± 2.5	19.0 ± 1.7

Table 3. Overall and seasonal means (± SE) of physical characteristics for regions in the Goose Creek estuary.

TEMPERATURE (° C)

Region	Overall	Fall	Winter	Spring	Summer
LOWER	23.6 ± 0.7	22.9 ± 0.7	11.0 ± 0.5	22.1 ± 1.2	29.2 ± 0.2
MIDDLE	23.5 ± 0.8	22.7 ± 0.7	10.6 ± 0.5	22.0 ± 1.1	29.1 ± 0.2
UPPER	23.2 ± 0.7	22.3 ± 0.6	10.9 ± 0.5	22.2 ± 0.7	29.2 ± 0.3

SALINITY (ppt)

Region	Overall	Fall	Winter	Spring	Summer
LOWER	7.8 ± 0.4	8.9 ± 0.5	2.9 ± 0.6	6.0 ± 0.8	9.0 ± 0.6
MIDDLE	4.3 ± 0.4	5.3 ± 0.6	1.0 ± 0.5	3.8 ± 1.0	4.6 ± 0.6
UPPER	1.2 ± 0.2	1.7 ± 0.3	0.0 ± 0.0	0.6 ± 0.4	1.2 ± 0.2

DISSOLVED OXYGEN (mg/l)

Region	Overall	Fall	Winter	Spring	Summer
LOWER	5.7 ± 0.2	5.8 ± 0.2	8.1 ± 0.3	6.6 ± 0.3	4.6 ± 0.2
MIDDLE	5.6 ± 0.2	5.5 ± 0.2	7.6 ± 0.5	6.7 ± 0.2	4.6 ± 0.2
UPPER	5.9 ± 0.1	5.5 ± 0.1	7.5 ± 0.5	6.7 ± 0.2	5.4 ± 0.2

Table 4. Overall and seasonal means (± SE) of nutrient concentrations for regions in the Goose Creek estuary.

ORTHOPHOSPHATE

Region	Overall	Fall	Winter	Spring	Summer
LOWER	1.4 ± 0.1	1.4 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	1.5 ± 0.1
MIDDLE	1.3 ± 0.1	1.1 ± 0.1	1.9 ± 0.6	1.1 ± 0.1	1.4 ± 0.1
UPPER	1.2 ± 0.1	1.2 ± 0.1	1.3 ± 0.2	1.3 ± 0.1	1.1 ± 0.1

AMMONIUM

Region	Overall	Fall	Winter	Spring	Summer
LOWER	10.2 ± 1.7	6.6 ±0.8	5.4 ±0.6	7.9 ±1.4	16.2 ±4.3
MIDDLE	8.2 ± 1.6	7.1 ±1.2	4.7 ±0.3	9.6 ±3.0	10.2 ±4.2
UPPER	10.3 ± 2.0	6.7 ±0.9	5.0 ± 0.4	8.6 ± 2.5	16.4 ±5.0

NITRATE

Region	Overall	Fall	Winter	Spring	Summer
LOWER	9.9 ± 0.6	12.0 ± 1.2	8.2 ± 0.8	8.8 ±1.3	8.6 ±1.0
MIDDLE	12.0 ± 0.9	13.1 ± 1.6	8.5 ± 1.9	6.5 ± 1.5	13.2 ± 1.4
UPPER	13.7 ± 0.9	16.7 ± 1.6	8.8 ±1.6	6.6 ±0.9	14.3 ±1.3

Table 5. **Overall and Seasonal Means of DOC, POC, and Chlorophyll by Regions along Goose Creek.**

REGION	DOC (mg/l) OVERALL	FALL	WINTER	SPRING	SUMMER
Lower	6.4 ± 0.3	6.0 ± 0.4	8.5 ± 0.9	7.8 ± 1.0	5.6 ± 0.5
Middle	9.0 ± 0.4	8.8 ± 0.8	11.8 ± 1.0	10.1 ± 0.9	7.9 ± 0.5
Upper	11.0 ± 0.3	11.0 ± 0.4	13.2 ± 1.1	12.1 ± 1.5	9.7 ± 0.5

REGION	POC (mg/l) OVERALL	FALL	WINTER	SPRING	SUMMER
Lower	2.4 ± 0.3	1.9 ± 0.5	7.8 ± 1.7	0.6 ± 0.2	1.8 ± 0.4
Middle	2.9 ± 0.5	1.9 ± 0.6	7.4 ± 2.1	1.3 ± 0.8	2.9 ± 0.7
Upper	3.12 ± 0.4	2.9 ± 0.6	7.0 ± 1.7	1.1 ± 0.5	2.4 ± 0.4

REGION	Chlorophyll (μg/l) OVERALL	FALL	WINTER	SPRING	SUMMER
Lower	5.2 ± 0.4	3.6 ± 0.3	1.1 ± 0.2	7.5 ± 3.1	7.8 ± 0.5
Middle	10.5 ± 1.4	7.4 ± 1.8	2.4 ± 1.0	15.5 ± 5.9	14.7 ± 2.4
Upper	21.3 ± 1.8	16.9 ± 2.3	3.9 ± 1.7	18.7 ± 3.9	33.3 ± 2.9

Table 6 Tidal Hydrology for the Brown Pond Marsh and the Mouth of Goose Creek

Location	Date	Tidal Range (cm)	Ebb Flow (10^6 l/tide)	Flood Flow (10^6 l/tide)	Tidal Prism (10^6 l/tide)
Brown Pond Marsh					
	2/27/93	140	10.6	9.3	10.0
	5/14/93	145	24.5	19.9	22.1
	7/27/93	182	36.2	34.7	35.5
	8/03/93	157	17.4	15.8	16.6
	9/24/93	155	26.7	28.4	27.5
	10/22/93	156	31.6	29.2	30.4
	11/19/93	146	43.7	38.0	40.8
	2/11/94	173	43.6	35.0	39.3
Mouth of Goose Creek			(10^9 l/tide)	(10^9 l/tide)	(10^9 l/tide)
	7/7/92		2.24	5.10	3.67
	10/3/92	141	2.46	3.38	2.92
	2/27/93	120	1.66	1.58	1.62
	5/14/93	145	2.32	2.30	2.31
	7/27/93	184	2.85	3.71	3.28
	8/03/93	167	2.29	2.41	2.35
	9/24/93	159	2.26	3.06	2.66
	11/19/93	162	3.17	3.63	3.40

Table 7 Nutrient Exchange at the Mouth of Goose Creek. Values in parentheses indicate "outliers" which differed from their nearest neighbor by more than 3 times the inter-quartile range.

Constituent	Date	Flow- Weighted Concentration (µg-at/l) Ebb	Flood	Net Tidal Flux (kg/tide)
Nitrate	7/7/92	3.0	2.5	22.4
	10/3/92	14.1	13.5	23.2
	2/27/93	9.8	9.9	-1.9
	5/14/93			
	7/27/93	13.7	12.6	47.7
	8/03/93	13.7	10.4	110.3
	9/24/93	21.1	19.0	75.9
	11/19/93	4.3	5.1	-39.9
			Median	23.2
			25%	10.3
			75%	61.6
Ammonium	7/7/92	5.6	4.5	55.4
	10/3/92	7.3	6.6	27.0
	2/27/93	4.3	3.5	17.1
	5/14/93			
	7/27/93	11.1	13.1	-91.3
	8/03/93	16.5	35.8	(-634.2)
	9/24/93	0.7	0.7	2.5
	11/19/93	6.1	6.6	-22.8
			Median	9.8
			25%	-16.4
			75%	24.5

Table 7 Continued

Constituent	Date	Flow- Weighted Concentration (µg/l) Ebb	Flood	Net Tidal Flux (kg/tide)
Chlorophyll-a	7/7/92	17.1	21.5	(-16.5)
	10/3/92	14.8	17.4	-7.5
	2/27/93	2.3	2.3	0
	5/14/93	2.5	1.5	2.4
	7/27/93	6.6	7.1	1.7
	8/03/93	7.8	8.8	-2.4
	9/24/93	2.0	2.4	-1.1
	11/19/93	2.8	2.9	-0.2
			Median	-0.22
			25%	-1.73
			75%	0.85

		(mg/l)		Metric Tons/Tide
DOC	7/7/92	4.7	8.6	-14.34
	10/3/92	6.2	4.7	4.33
	2/27/93	11.4	6.4	8.08
	5/14/93	5.7	6.7	-2.37
	7/27/93	2.8	2.9	-0.52
	8/03/93	9.6	6.6	7.10
	9/24/93	4.5	4.7	-0.47
	11/19/93	13.2	12.3	3.15
			Median	1.34
			25%	-0.98
			75%	5.02

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APPENDIX A

ANALYTICAL AND STATISTICAL PROCEDURES

Sample Processing and Analysis

Samples for the determination of the dissolved inorganic nutrients (nitrate + nitrite, ammonium, and orthophosphate) were filtered through rinsed 0.45 μm glass microfiber filters (Whatman GF/F). The filtrate was then poured into 20 ml polyethylene scintillation vials. Since nitrite is typically the minor fraction of oxidized nitrogen, nitrate-nitrite will be referred to as nitrate. Samples for ammonium were preserved with .1 % (w/v) phenol (Degobbis 1973). Samples for nitrate were preserved with 2 % (w/v) mercuric chloride. These samples were refrigerated at 4 ^{o}C up to 2 weeks before analysis. Orthophosphate was analyzed within 48 hrs. of sample collection; therefore, samples were not preserved. Ammonium concentrations were determined by the phenol hypochlorite method (Solarzano 1969), nitrate by the cadmium reduction method (APHA 1985), and orthophosphate by the acid molybdate method (Murphy and Riley 1962). All analyses were performed using a segmented flow auto analyzer (Orion Scientific). Dissolved organic nitrogen and total nitrogen were determined on filtered and unfiltered samples, respectively, using a spectrophotometric technique based on the alkaline persulfate digestion technique (Johnes and Heathwaite 1992). Duplicate analyses were performed on approximately 10% of all samples. The mean difference between duplicates were 0.3 $\pm$ 0.1 μg-at/l for orthophosphate, 1.3 $\pm$ 0.3 μg-at/l for ammonium, and 0.7 $\pm$ 0.2 μg-at/l for nitrate.

Chlorophyll-a was determined fluorometrically (Turner 10-AU) after a freeze-thaw acetone extraction procedure described by Glover and Morris (1979).

Organic carbon was determined by high temperature catalytic combustion using a Dohrman DC-190 carbon analyzer. Analyses were performed on filtered (pre-combusted GF/F glass fiber filters) for dissolved organic carbon (DOC) and on un-filterd samples for total organic carbon. Particulate organic carbon (POC) was taken as the TOC-DOC.

Statistical Analysis

Prior to statistical analysis for significant patterns, data for each parameter were checked for normality. Dissolved oxygen, salinity, and temperature were found to be normally distributed. Nitrogen, phosphorus, carbon and chlorophyll data were normalized through log (ln) transformation. The Studentized Residual test (SAS 1985) was used to identify statistical outliers defined as data points which deviated from the mean of each class of data by more than 3 standard deviations. Less than 5% of all data were identified as outliers and were removed from basic statistical comparisons.

Statistical differences due to station, tide, month, season and region were determined by multivariate analysis of co-variance (PROC GLM, SAS, 1985). Seasons were defined as follows: Fall (September, October, and November), Winter (January, February, March), Spring (April, May, June), and Summer (June, July, and August). Estuarine regions were designated as lower, middle and upper. The lower region was within 5 km of the mouth, where average high tide salinities were > 8 $^{o}/oo$. The middle region was 5-10 km upstream where average high tide salinities were 5-8 $^{o}/oo$. The upper region was largely tidal freshwater 10-15 km upstream where average high tide salinity was < 5 $^{o}/oo$. Significant differences were identified at an α-level of .05 and suggested differences were identified at α = 0.1. Pairwise multiple contrasts were used to identify specific differences between seasons, regions, and contributing sources. For multiple contrast analyses, a protected α-level of α/N was used where

α = .05 for statistical significance, or 0.1 for suggested difference
N = (n(n-1))/2; where n was the specific number of contrast categories

The Pearson correlation procedure was used determine the association between variables.

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APPENDIX B

RATING CURVE DEVELOPMENT FOR THE GOOSE CREEK RESERVOIR DAM

H. McKellar and R. Rao

Surface water discharge from the Goose Creek Reservoir into the estuary is driven by the hydraulic head difference between the water level in the lake (lake stage) and the elevation of the spillway crest. The main spillway is 200 ft wide with a crest elevation of 7.0 ft MSL. During high discharges and elevated lake stages, additional discharge occurs through a 760 ft wide spillway with a crest elevation of 7.5 ft MSL. Down-gradient from the crests, the spillway slopes 6.67% (1:15) for a 15 ft. length and then slopes 32.9% (6:14.5) for a14.5 ft length forming a 5.5-6.0 ft drop to the high water level in the upper Goose Creek estuary.

If discharge through the spillway reaches critical flow conditions, then a theoretical relationship can be developed between the lake stage and spillway discharge. A basic test for critical flow conditions is to compare the normal discharge depth (d_n) with critical discharge depth (d_c). If $d_n < d_c$ for a wide range of discharge conditions then flow becomes critical as it flows over the crest and a theoretical rating curve can be developed.

According to the Manning's equation for normal flow,

$$Q = A\ 1.49/\eta * R^{2/3}\ S^{1/2} \qquad (1)$$

where Q = discharge (ft^3/sec),
A = cross-section of flow area, = d_n w
where d_n = normal depth (ft) and w = flow width (ft),
η = roughness coefficient, = .017 for un-troweled concrete (Simon 1986),
R = hydraulic radius (approximately equal to the normal depth (d_n) for wide channels (Simon 1986), and
S = slope (.0667)

By substituting d_n for R and d_n(w) for A, the normal depth for a wide range of flow conditions can be calculated as

$$d_n^{5/3} = Q/(w\ (1.49/\eta)\ S^{1/2}) \qquad (2)$$

For <u>critical</u> flow conditions,

$$Q = A\,(g\,d_c)^{1/2} \tag{3}$$

where g = gravity, 32.2 ft/sec^2, and
d_c = critical depth (ft).

Solving for d_c yields

$$d_c^{3/2} = Q/(w\,g^{1/2}) \tag{4}$$

According to these relationships (Eqns. 2 and 4), discharge over the spillway crest reaches critical flow for a wide range of flow conditions (1-1000 cfs), thereby allowing a theoretical stage-discharge relationship to be developed.

If discharge through the spillway reaches critical flow then

$$H = d_c + v_c^2/2g \tag{5}$$

where H = the difference between the lake stage and the spillway crest,
d_c = $Q/(w\,g^{1/2})$, and
v_c = $Q/(w\,d_c)$.

Using these relationships, a series of stage-discharge points were computed and regressed to form the following equations:

(7) $$Q_{lo} = 617\,H^{1.5}, \text{ and}$$

$$Q_{hi} = 2340\,H^{1.5} \tag{8}$$

where Q_{lo} is discharge through the 200 ft low-crest section (cfs), and
Q_{hi} is the discharge through the 760 ft high crest section (cfs).

Total discharge from the Goose Creek Reservoir was taken as $Q_{lo} + Q_{hi}$

APPENDIX C

SIMULATION OF FLOW IN THE GOOSE CREEK USING THE BRANCH MODEL

By Rajesh P. Rao

INTRODUCTION

Computational hydraulics is a relatively new and emerging discipline which combines theoretical and experimental hydraulics. This discipline requires experimental determination of parameters used in theoretical hydraulic concepts, which are combined with knowledge in computer science to form an effective tool for water resource study.

The Branch Model is a one dimensional numerical model for simulating flows in open channels (Schaffranek et al. 1981). It is based on one-dimensional partial differential equations governing unsteady flow and can be applied to channels under the influence of tides. The source code of this model is written in FORTRAN and is comprised of a MAIN Program and eight subroutines. The primary functions of the MAIN Program are to control the model input and output, initiate and terminate a simulation, retrieve data from the data base whenever required, and to solve the partial differential equations governing the flow

The eight subroutine programs assist the MAIN Program in performing the above tasks. The Branch model uses certain other utility programs like the Time Dependent Data System TDDS, which stores data in the Time Dependent Data Base TDDB. This data can be retrieved using the MAIN Program for input into the model and the Channel Geometry Analysis Program CGAP, for processing the channel cross section data. This program calculates area-top width relations at different stages.

Two main assumptions are made while implementing the Branch model: 1. The Mannings equation is applicable to unsteady flow conditions and is hence used for calculating flows and 2. The flow is simulated as flow in straight channels (in longitudinal sense).

Model implementation requires input of physical and hydraulic properties of the channel. Firstly, the channel geometry is divided into smaller branches which are further divided into segments so that the flow can be simulated as flow in open straight channels. The lengths and the cross sectional geometry comprising of stage-area-topwidth should be calculated at each of these segments for a range of stage values. These data were obtained from USGS topographic maps, NOAA nautical charts and from direct field measurements.

Hydraulic parameters such as flow resistance coefficient, momentum coefficient, water surface drag, wind sheer need to be estimated for the system under consideration. Since these parameters are not very easily quantifiable, reasonable approximation is allowed in determining them. Of these above mentioned parameters, the flow resistance coefficient is most difficult to quantify. Since the Mannings equation **U=1.49*R^(.667)*S^(.5)/η** is assumed to be applicable to unsteady flow conditions, η represents the flow resistance coefficient which is a function of channel roughness. The flow resistance coefficient represented a major calibration parameter for the model.

Accurate flow simulation also depends on the determination of the momentum coefficient. It plays a vital role when the system under consideration has cross sectional irregularities. It is always greater or equal to one and for most natural channels is around 1.06. The water surface drag coefficient is induced as a forcing function in the model in order to account for wind induced currents. The coefficient depends on the depth of flow, height of wind generated waves and its value ranges between 0.0015 to 0.0026. Flow simulation by mathematical models require that the initial and boundary value data be given. Initial boundary values of known quantities like water surface elevations and discharges must be supplied to the model.

OBJECTIVES

The main objectives of this work were to:

1. Configure the model for the Goose Creek estuary, South Carolina,

2. Calibrate the model based on flows measured in the field over 2 complete tidal cycles.

3. Implement the model for monthly sampling dates in order to calculate water flux at the mouth of the estuary

MODEL IMPLEMENTATION

Implementation of the Branch model for the Goose Creek estuary was accomplished in collaboration with Paul Conrads of the US Geological Survey (Columbia, SC). The estuary was divided into two main branches (1), from Rhett Bridge to New Tenant Pond and branch and (2) from New Tenant Pond to the mouth (Army Depot). Each of these branches was subdivided into five segments. Calibration measurements of velocities and corresponding depths were made at the Rhett Bridge and at the mouth on two complete tidal cycles (10/03/92 and 12/04/92). Depth and velocity profiles were measured every 1.5 hrs using a Price AA current meter. Stream stage data were obtained from water level recorders at the mouth (USGS gauging station 02170675) and at Rhett Bridge (USGS gauging station 02172066). These data were incorporated into the TDDB (Time Dependent Data Base). Instantaneous stream stage values were corrected to National Geodetic Vertical Datum (NGVD) by applying a datum correction (-8.01 ft at the mouth and -6.99 ft at the Rhett Bridge). Corresponding stage and the channel top width data obtained from the USGS maps for these two stations was used as input in the CGAP program to extrapolate the Stage-area-topwidth relationship for different stages at the remaining segments (the maximum top width is the top width at bank full conditions). The lengths of these segments were calculated from the USGS maps using a rotometer.

MODEL CALIBRATION AND VERIFICATION

Major calibration parameters are the flow resistance coefficient η, and channel geometry. The value of η used ranged from 0.025 to 0.030 (refer to the input file). Since the exact channel geometry was not known, rough estimates were made from USGS maps and navigation charts. An excessive cross sectional area that results from entering too large a value for stage in the stage versus cross section table, results in amplification of flows. On the other hand too small a value for stage causes the reverse effect. An adjustment to correct the error can be made in the model by using datum correction input parameter to adjust the stage value. The datum correction factor used for calibrating the model varied from 2.50 ft at Rhett Bridge (section 1, branch 1) to 1.74 ft at the mouth (section 5, branch 2). An additional storage term was incorporated which accounts for water being stored in the salt marshes around the creek when the stage exceeds bank full condition for calibration purposes. The Data Input File for the calibrated model is provided in Table C1.

The model was calibrated using the flows measured on 12/04/92 and verified with the 10/03/92 flow measurements. The flows generated by the model were used to calculate the ebb and flood volumes of water over a tidal cycle. These numbers were compared with the integrated values of ebbing and flooding water actually measured in the field over that tidal cycle. The difference in the model generated and actual measured flows was within 10-15% (Fig. C1, C2). The model was subsequently used to calculate flows at the Army Depot and Rhett Bridge for monthly sampling dates to calculate mass fluxes at these stations.

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APPENDIX D

STATISTICAL TABLES FOR TEMPORAL AND SPATIAL PATTERNS OF WATER QUALITY DISTRIBUTIONS

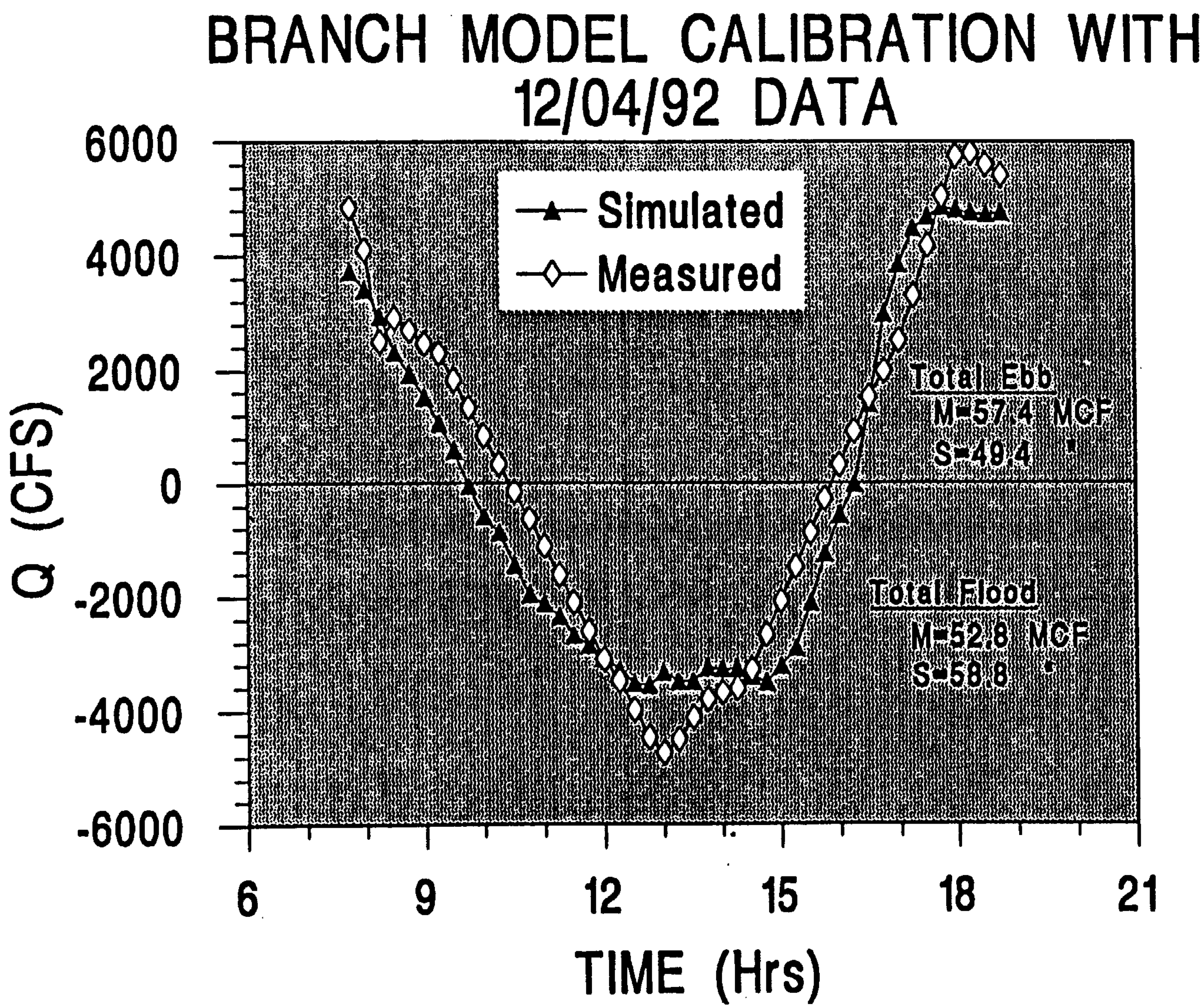

Figure C1. **Branch model calibration.** M = measured, S = simulated (MCF = million cubic feet)

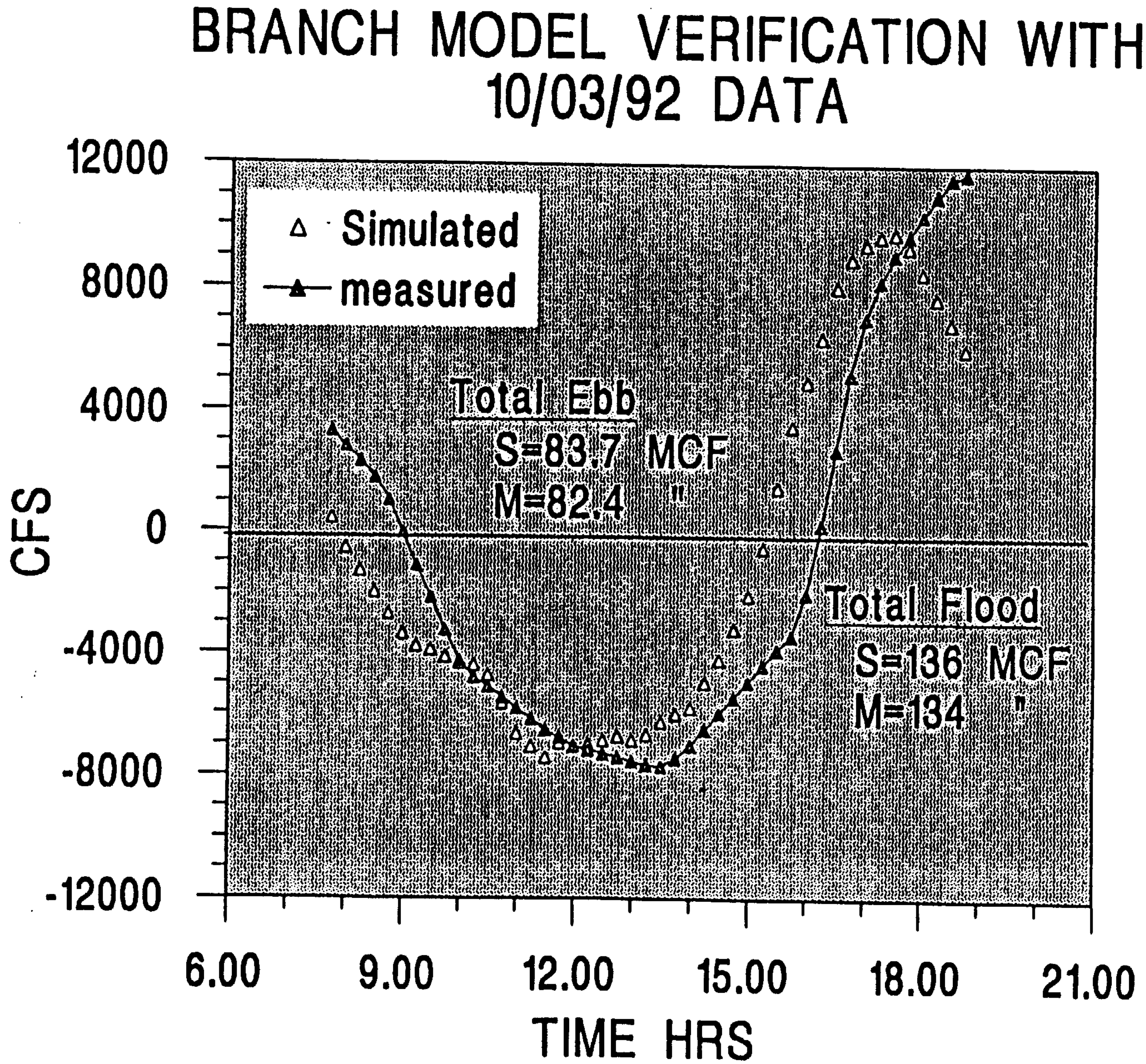

Figure C2. Branch model verification

Table C1. Data Input File for the Branch Model

INDEX

ROW1-Network Name Record

Row2-Computation Control Card

```
EN      -English Input Units
 2      -# of Branches
 3      -# of Junctions
 2      -# of external boundries
EN      -English Output Units
15      -Simulation time incrment in minutes
 1      -Theta(finite differerce weighing factor)
0.0026 -Water surface drag coefficient
1.9617 -Water density
```

ROW3-Branch Identification card

ROW4-Initial Condition card

```
1.0     -Initial stage value
100.0   -Initial discharge value
4752    -Segment length
59.0    -Water temperature in Fahrenheit
.0250   -Resistance coefficient
```

ROW5-Cross-sectional geometry cards

```
12      -# of cross-sectional geometry data cards.
col1    -stage
col2    -cross-sectional area at specified stage in sq ft.
col3    -top width of cross section at specified stage.
col4    -storage at that perticular stage.
2.5     -Datum correction input parameter in ft.
```

C:\BRANCH\GS1.CTL 5/19/94

```
GooseCreek from Army Depot (021720675) to Rhett Bridge (02172066)
EN 2 3 2     ENO  53300111 0 0 0151.   80. .050  .00.00261961710000000   .00001 00
 1 2 5Rhett St   to NTO                                        00000
     1.000    100.00               4752.00     59.000.02500

11  xsec 1                                                          2.500
    -5.000    224.236    98.240
    -4.000    333.811   120.680
    -3.000    464.218   137.587
    -2.000    608.124   150.224
    -1.000    764.669   162.862
      .000    933.849   175.500
     1.000   1109.349   175.500  1336.051
     2.000   1284.849   175.500  1344.148
     3.000   1460.349   175.500  1352.250
     4.000   1635.849   175.500  1360.351
     5.000   1811.349   175.500  1368.449
     1.00     1000.00              5280.00     59.000.02500

11 xsec 2                                                           2.480
    -5.000    764.225   133.770
    -4.000    909.492   153.945
    -3.000   1070.962   169.479
    -2.000   1246.462   181.440
    -1.000   1433.842   193.400
      .000   1633.900   209.740
     1.000   1843.640   209.740  1226.043
     2.000   2053.380   209.740  1234.144
     3.000   2263.120   209.740  1242.243
     4.000   2472.860   209.740  1250.343
     5.000   2682.600   209.740  1258.445
     1.00     1000.00              5280.00     59.000.02500

11 xsec 3                                                           2.460
    -5.000   1230.129   164.432
    -4.000   1406.197   162.684
    -3.000   1594.470   197.001
    -2.000   1797.158   208.372
    -1.000   2011.216   219.744
      .000   2237.913   239.283
     1.000   2477.196   239.283  1131.128
     2.000   2716.479   239.283  1139.228
     3.000   2955.762   239.283  1147.328
     4.000   3195.045   239.283  1155.429
     5.000   3434.328   239.283  1163.527
     1.00     1000.00              3394.28     59.000.02500

11 xsec 4
    -5.000  1696.043   195.071
    -4.000  1902.903   211.351
    -3.000  2117.977   224.522
    -2.000  2347.892   235.305
    -1.000  2588.589   246.090
      .000  2841.926   268.826
     1.000  3110.752   268.826  1036.2
     2.000  3379.578   268.826  1044.3
     3.000  3648.404   268.826  1052.4
     4.000  3917.230   268.826  1060.5
     5.000  4186.056   268.826  1068.6
     1.00    1000.00

11 xsec 5
    -5.000  1995.623   214.803
    -4.000  2222.284   229.806
    -3.000  2454.511   242.217
    -2.000  2702.013   252.623
    -1.000  2959.841   263.031
      .000  3230.307   287.822
     1.000  3518.129   287.822    975.18
     2.000  3805.951   287.822    983.28
     3.000  4093.773   287.822    991.38
     4.000  4381.595   287.822    999.48
     5.000  4669.417   287.822   1007.58
 2 3 5NTO to Army Depot
     1.000  10000.00               1885.7

11  NTO
    -5.000  1995.623   214.803
    -4.000  2222.284   229.806
    -3.000  2454.511   242.217
    -2.000  2702.013   252.623
    -1.000  2959.841   263.031
      .000  3230.307   287.822
     1.000  3518.129   287.822    975.18
     2.000  3805.951   287.822    983.28
     3.000  4093.773   287.822    991.38
     4.000  4381.595   287.822    999.48
     5.000  4669.417   287.822   1007.582
     1.00    1000.00               5280.0

11  xsec 2
    -5.000  2161.953   225.748
    -4.000  2399.607   240.053
    -3.000  2641.483   252.041
```

Table C1. Continued

```
                                                          C:\BRANCH\GS1.CTL 5/19/94
        -2.000  2898.625   262.237
        -1.000  3165.963   272.437
          .000  3445.939   298.369
         1.000  3744.308   298.369   941.298
         2.000  4042.677   298.369   949.397
         3.000  4341.046   298.369   957.498
         4.000  4639.415   298.369   965.597
         5.000  4937.784   298.369   973.699
         1.00    1000.00             5280.00      59.000.02500

  11    xsec 3                                                                  1.800
        -5.000  2627.862   256.407
        -4.000  2896.313   268.757
        -3.000  3164.991   279.561
        -2.000  3449.358   289.172
        -1.000  4067.336   298.783
          .000  4049.953   327.913
         1.000  4377.866   327.913   846.381
         2.000  4705.779   327.913   854.481
         3.000  5033.692   327.913   862.581
         4.000  5361.605   327.913   870.683
         5.000  5689.518   327.913   878.781
         1.00    1000.00             5280.00      59.000.02500

  11    xsec 4                                                                  1.780
        -5.000  3091.071   287.064
        -4.000  3393.018   297.459
        -3.000  3688.498   307.080
        -2.000  4000.092   316.080
        -1.000  4320.710   325.130
          .000  4653.966   357.456
         1.000  5011.422   357.456   751.466
         2.000  5368.878   357.456   759.565
         3.000  5726.334   357.456   767.602
         4.000  6083.790   357.456   775.831
         5.000  6441.246   357.456   783.867
         1.00    1000.00

  11    xsec 5                                                                  1.760
        -5.000  3559.680   317.724
        -4.000  3881.624   326.162
        -3.000  4212.000   334.619
        -2.000  4550.826   343.039
        -1.000  4898.084   351.477
          .000  5257.980   387.000
         1.000  5644.980   387.000   656.550
         2.000  6031.980   387.000   664.649

                                                                   Page 3

         3.000  6418.980   387.000   672.750
         4.000  6805.980   387.000   680.851
         5.000  7192.980   387.000   698.949

  Z 1      2172066  FROM= 92/12/03 08:00  TO= 92/12/04 18:45    96  -6.99     1 1
  Z 3      21720675 FROM= 92/12/03 08:00  TO= 92/12/04 18:45    96  -8.01     2 5
  Q 3      2172066  FROM= 92/12/04 07:45  TO= 92/12/04 18:00    96            1 1
```

Table D1. General linear model for water temperature

Source	p-value
Station	.1325
Tide	.0001•
Month	.0001•
Station•Tide	.3978
Station•Month	.2029
Tide•Month	.0001•

Overall p-value = .0001; R^2 = .99; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean water temperature in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.6703	.8333	.6511	.9556	.6704
Lower vs. Upper	.6947	.5001	.8631	.9656	.8498
Middle vs. Upper	.9428	.6906	.7650	.9250	.8069

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean water temperature in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001•	.0001•	.0001•	.0001•
Fall vs. Spring	.3358	.4087	.4791	.8486
Fall vs. Summer	.0001•	.0001•	.0001•	.0001•
Winter vs. Spring	.0001•	.0001•	.0001•	.0001•
Winter vs. Summer	.0001•	.0001•	.0001•	.0001•
Spring vs. Summer	.0001•	.0001•	.0001•	.0001•

(•) statistically significant at alpha =.05/6 = .008.

Table D2. General linear model for salinity

Source	p-value
Station	.0001•
Tide	.0001•
Month	.0001•
Station•Tide	.0001•
Station•Month	.0001•
Tide•Month	.0001•

Overall p-value = .0001; R^2 = .98; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean salinity in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring[a]	Summer
Lower vs. Middle	.0001•	.0001•	.0220	.1352	.0001•
Lower vs. Upper	.0001•	.0001•	.0006•	••	.0001•
Middle vs. Upper	.0001•	.0001•	.2134	••	.0001•

(•) statistically significant at alpha =.05/3 = .017, [a] insufficient data to estimate.

P-values for seasonal contrasts for mean salinity in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001•	.0001•	.0001•	.0003•
Fall vs. Spring	.0001•	.0013•	.0847	.0390
Fall vs. Summer	.2190	.8691	.2763	.0930
Winter vs. Spring	.0016•	.0064•	.0506	.5273
Winter vs. Summer	.0001•	.0001•	.0002•	.0139
Spring vs. Summer	.0018•	.0010•	.2791	.2472

(•) statistically significant at alpha =.05/6 = .008.

Table D3. General linear model for dissolved oxygen

Source	p-value
Station	.0308•
Tide	.0001•
Month	.0001•
Station•Tide	.0706
Station•Month	.0001•
Tide•Month	.0003•

Overall p-value = .0001; R^2 = .92; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean dissolved oxygen in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.5912	.4741	.5925	.7731	.6644
Lower vs. Upper	.7818	.4009	.4402	.7557	.0005•
Middle vs. Upper	.4330	.9551	.8735	.9921	.0042•

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean dissolved oxygen in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001•	.0001•	.0001•	.0001•
Fall vs. Spring	.0001•	.0232	.0073•	.0017•
Fall vs. Summer	.0001•	.0001•	.0030•	.7183
Winter vs. Spring	.0002•	.0014•	.0897	.0898
Winter vs. Summer	.0001•	.0001•	.0001•	.0001•
Spring vs. Summer	.0001•	.0001•	.0001•	.0008•

(•) statistically significant at alpha =.05/6 = .008.

Table D4. General linear model for ln PO4

Source	p-value
Station	.0022•
Tide	.4715
Month	.0001•
Station•Tide	.1896
Station•Month	.4024
Tide•Month	.0847

Overall p-value = .0001; R^2 = .75; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean PO4 in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.5371	.0618	.1169	.3881	.5980
Lower vs. Upper	.1062	.0613	.7283	.9058	.0026•
Middle vs. Upper	.4308	.9079	.1913	.3327	.0212

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean PO4 in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.1439	.3390	.0462	.2189
Fall vs. Spring	.1409	.8994	.4048	.1534
Fall vs. Summer	.0790	.2251	.0224	.8952
Winter vs. Spring	.9786	.4290	.3037	.8375
Winter vs. Summer	.8439	.0873	.6381	.2550
Spring vs. Summer	.8208	.4748	.4147	.1801

(•) statistically significant at alpha =.05/6 = .008.

Table D5. Means for PO4 in the headwater, point source discharge, and forested and urban tributary stations, by season, for period June 1992 - November 1993.

	Fall	Winter	Spring	Summer
Headwater				
Goose Creek reservoir	2.5 ± 1.7	1.6 ± 0.4	4.0 ± 0.6	1.9 ± 0.3
Point Source				
Charleston Commissioners of Pubic Works	0.9 ± 0.3	2.1 ± 0.8	0.4 ± 0.1	1.3 ± 0.3
Hanahan Wastewater Treatment plant	68.2 ± 14.0	86.7 ± 39.3	100 ± 0.00	287.4 ± 153.7
Tributary				
Forested				
Brown Pond (outflow)	0.4 ± 0.2	••	5.1 ± 3.7	0.7 ± 0.1
New Tenant Pond (inflow)	1.5 ± 0.7	••	1.2 ± 0.3	1.2 ± 0.2
New Tenant Pond (outflow)	0.9 ± 0.3	1.2 ± 0.3	1.5 ± 0.2	2.4 ± 0.8
Urban				
South Turkey Creek	0.9 ± 0.1	1.1 ± 0.2	2.2 ± 1.2	1.2 ± 0.2
Turkey Creek	1.5 ± 0.6	2.0 ± 0.2	••	1.4 ± 0.3
Hanahan Creek	1.4 ± 0.4	1.4 ± 0.0	1.8 ± 0.2	2.2 ± 0.4

•• Not enough data

Table D6. General linear model for ln NH4

Source	p-value
Station	.8011
Tide	.5108
Month	.0001•
Station•Tide	.4595
Station•Month	.6750
Tide•Month	.5873

Overall p-value = .0001; R^2 = .75; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean NH4 in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.3821	.7667	.6617	.8808	.1120
Lower vs. Upper	.3354	.8359	.8488	.6078	.2486
Middle vs. Upper	.9960	.6334	.7830	.7498	.6143

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean NH4 in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.7640	.9309	.6195	.9596
Fall vs. Spring	.3480	.3193	.6482	.6968
Fall vs. Summer	.2699	.0335	.5226	.7571
Winter vs. Spring	.3104	.3850	.4374	.7132
Winter vs. Summer	.2757	.1171	.9732	.7802
Spring vs. Summer	.8867	.5819	.3648	.8657

(•) statistically significant at alpha =.05/6 = .008.

Table D7. Means for NH_4 (ug-at/l) in the headwater, point source discharge, and forested and urban tributary stations, by season, for period June 1992 - November 1993.

	Fall	Winter	Spring	Summer
Headwater				
Goose Creek reservoir	4.3 ± 1.4	3.5 ± 0.7	1.9 ± 0.2	9.9 ± 3.9
Point Source				
Charleston Commissioners of Public Works	6.8 ± 2.9	3.0 ± 0.9	5.6 ± 3.0	23.7 ± 8.2
Hanahan Wastewater Treatment plant	186.1 ± 144.8	208.4 ± 197.6	216 ± 124	206.5 ± 121.1
Tributary				
Forested				
Brown Pond (outflow)	3.8 ± 2.5	••	4.8 ± 3.3	36.4 ± 6.1
New Tenant Pond (inflow)	13.0 ± 7.7	••	2.8 ± 0.7	22.6 ± 13.3
New Tenant Pond (outflow)	3.9 ± 0.9	1.9 ± 1.1	2.5 ± 1.3	11.7 ± 6.3
Urban				
South Turkey Creek	31.4 ± 5.3	30.6 ± 14.9	21.9 ± 12.3	14.0 ± 2.1
Turkey Creek	18.9 ± 2.2	16.7 ± 10.8	16.9 ± 12.5	19.2 ± 4.7
Hanahan Creek	12.2 ± 2.6	11.6 ± 3.9	10.8 ± 6.2	31.5 ± 7.7

•• Not enough data

Table D9. Means for NN in the headwater, point source discharge, and forested and urban tributary stations, by season, for period June 1992 - November 1993.

	Fall	Winter	Spring	Summer
Headwater				
Goose Creek reservoir	5.5 ± 4.8	2.0 ± 0.8	1.2 ± 0.1	2.1 ± 0.8
Point Source				
Charleston Commissioners of Public Works	11.2 ± 6.4	15.4 ± 3.4	8.1 ± 0.3	21.2 ± 1.7
Hanahan Wastewater Treatment plant	443 ± 128.3	215 ± 16	..	761 ± 211.3
Tributary				
Forested				
Brown Pond (outflow)	0.5 ± 0.2	..	1.4 ± 1.4	0.8 ± 0.3
New Tenant Pond (inflow)	4.7 ± 1.6	..	2.2 ± 2.2	1.8 ± 1.0
New Tenant Pond (outflow)	1.5 ± 0.5	1.5 ± 0.3	2.2 ± 2.2	4.7 ± 2.0
Urban				
South Turkey Creek	57.1 ± 7.9	8.8 ± 0.6	24.6 ± 6.6	56.1 ± 23.2
Turkey Creek	33.3 ± 7.3	14.7 ± 4.4	21.8 ± 9.1	26 ± 4.1
Hanahan Creek	17.8 ± 3.4	15.6 ± 0.5	8.5 ± 2.8	15.5 ± 4.0

.. Not enough data

Table D10. Pearson correlation coefficents for all data collected for the Goose Creek estuary from June 1992 to November 1993.

<u>Water Quality & Flow Variables</u>

Temp., Temperature; Sal., Salinity; DO, Dissolved Oxygen; NN, Nitrate; NH4, Ammonium; PO4, Orthophosphate; D7FL GCR Average 7-day flow from the Goose Creek reservoir; D7FL CCPW, Average 7-day flow from the Charleston Commissioners of Public Works; D7FL HWT, Average 7-day flow from the Hanahan Wastewater Treatment plant; Total D7FL,Total average 7-day flow from GCR, CCPW, and HWT.

r = Sample correlation coefficient (+ for positive correlation and - for negative correlation); p = p-value (• statistically significant at p-value < .05) ; ns = no significant correlation; -- no data; N = number of observations.

	Temp.	Sal.	DO	ln NH4	ln NN	ln PO4	D7FL GCR	D7FL CCPW	D7FL HWT	Total D7FL	
Temp.		.265	-.698	.063	.224	.129	-.407	.392	-.341	-.306	r
		•	•	ns	•	•	•	•	•	•	p
		239	245	241	236	241	144	248	248	248	N
Sal.			-.162	.187	-.001	.156	-.288	.200	-.205	-.147	r
			•	•	ns	•	•	•	•	ns	p
			237	234	229	235	136	239	239	239	N
DO				.006	-.140	.020	.396	-.146	.404	.377	r
				ns	•	ns	•	•	•	•	p
				239	234	239	142	245	245	245	N
ln NH4					.119	.104	-.223	.599	-.172	-.064	r
					ns	ns	•	•	•	ns	p
					231	236	138	241	241	241	N
ln NN						.116	-.406	.103	-.023	-.041	r
						ns	•	ns	ns	ns	p
						231	134	236	236	236	N
ln PO4							.160	.139	.219	.152	r
							•	•	•	•	p
							140	241	241	241	N
D7FL GCR								-.276	.935	.999	r
								•	•	•	p
								144	144	144	N
D7FL CCPW									-.300	-.136	r
									•	•	p
									254	254	N
D7FL HWT										.890	r
										•	p
										254	N

Table D13 . General linear model In POC

Source	p-value
Station	.3314
Tide	.0533
Month	.0001•
Station•Tide	.0208•
Station•Month	.5512
Tide•Month	.0412•

Overall p-value = .0001; R^2 = .70; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean POC in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.8700	.8269	.9717	.8831	.9364
Lower vs. Upper	.8789	.3078	.3920	.8380	.6238
Middle vs. Upper	.9819	.2587	.4226	.9621	.7150

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean POC in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001•	.0007•	.0151	.2527
Fall vs. Spring	.0019•	.0858	.2395	.0166
Fall vs. Summer	.4711	.4619•	.4851	.9520
Winter vs. Spring	.0001•	.0001•	.0038•	.0039•
Winter vs. Summer	.0008•	.0039•	.0512	.2389
Spring vs. Summer	.0004•	.0269•	.0982	.0194

(•) statistically significant at alpha =.05/6 = .008.

Table D12. General linear model ln DOC

Source	p-value
Station	.0001
Tide	.0001•
Month	.0001•
Station•Tide	.0001•
Station•Month	.0072•
Tide•Month	.0001•

Overall p-value = .0001; R^2 = .88; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean DOC in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.0001•	.0001•	.0410	.0284	.0010•
Lower vs. Upper	.0001•	.0001•	.0068•	.0023•	.0001•
Middle vs. Upper	.0048•	.0002•	.5882	.2998	.1266

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean DOC in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001•	.0025•	.0018•	.2180
Fall vs. Spring	.0187	.0386	.0709	.5733
Fall vs. Summer	.0218	.2802	.4673	.0468
Winter vs. Spring	.1874	.4119	.2435	.6179
Winter vs. Summer	.0001•	.0002•	.0004•	.0081
Spring vs. Summer	.0001•	.0053•	.0223	.0551

(•) statistically significant at alpha =.05/6 = .008.

Table D13 . General linear model ln POC

Source	p-value
Station	.3314
Tide	.0533
Month	.0001*
Station*Tide	.0208*
Station*Month	.5512
Tide*Month	.0412*

Overall p-value = .0001; R^2 = .70; (*) statistically significant at alpha = .05.

P-values for regional contrasts for mean POC in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.8700	.8269	.9717	.8831	.9364
Lower vs. Upper	.8789	.3078	.3920	.8380	.6238
Middle vs. Upper	.9819	.2587	.4226	.9621	.7150

(*) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean POC in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001*	.0007*	.0151	.2527
Fall vs. Spring	.0019*	.0858	.2395	.0166
Fall vs. Summer	.4711	.4619*	.4851	.9520
Winter vs. Spring	.0001*	.0001*	.0038*	.0039*
Winter vs. Summer	.0008*	.0039*	.0512	.2389
Spring vs. Summer	.0004*	.0269*	.0982	.0194

(*) statistically significant at alpha =.05/6 = .008.

Table D11. General linear model for ln Chorophyll

Source	p-value
Station	.0001•
Tide	.0001•
Month	.0001•
Station•Tide	.0919
Station•Month	.1717
Tide•Month	.0001•

Overall p-value = .0001; R^2 = .88; (•) statistically significant at alpha = .05.

P-values for regional contrasts for mean chlorophyll in the Goose Creek estuary over the fifteen month sampling period and for each season. Regional units are Lower, Middle, and Upper.

Contrast	All 15 months	Fall	Winter	Spring	Summer
Lower vs. Middle	.0001•	.0836	.3240	.0967	.0001•
Lower vs. Upper	.0001•	.0001•	.3014	.0277	.0001•
Middle vs. Upper	.0005•	.0002•	.9523	,6371	.0001•

(•) statistically significant at alpha =.05/3 = .017.

P-values for seasonal contrasts for mean chlorophyll in the Goose Creek estuary over all eight main channel stations combined and for each region.

Contrast	All 8 stations	Lower	Middle	Upper
Fall vs. Winter	.0001•	.0001•	.0092	.0001•
Fall vs. Spring	.3112	.0851	.2536	.2146
Fall vs. Summer	.0001•	.0001•	.0014•	.0006•
Winter vs. Spring	.0001•	.0001•	.0026•	.0001•
Winter vs. Summer	.0001•	.0001•	.0001•	.0001•
Spring vs. Summer	.0001•	.0001•	.2238	.0003•

(•) statistically significant at alpha =.05/6 = .008.

Table D10. Pearson correlation coefficents for all data collected for the Goose Creek estuary from June 1992 to November 1993.

Water Quality & Flow Variables

Temp., Temperature; Sal., Salinity; DO, Dissolved Oxygen; NN, Nitrate; NH4, Ammonium; PO4, Orthophosphate; D7FL GCR Average 7-day flow from the Goose Creek reservoir; D7FL CCPW, Average 7-day flow from the Charleston Commissioners of Public Works; D7FL HWT, Average 7-day flow from the Hanahan Wastewater Treatment plant; Total D7FL,Total average 7-day flow from GCR, CCPW, and HWT.

r = Sample correlation coefficient (+ for positive correlation and - for negative correlation); p = p-value (• statistically significant at p-value $< .05$) ; ns = no significant correlation; -- no data; N = number of observations.

	Temp.	Sal.	DO	ln NH4	ln NN	ln PO4	D7FL GCR	D7FL CCPW	D7FL HWT	Total D7FL	
Temp.		.265	-.698	.063	.224	.129	-.407	.392	-.341	-.306	r
		•	•	ns	•	•	•	•	•	•	p
		239	245	241	236	241	144	248	248	248	N
Sal.			-.162	.187	-.001	.156	-.288	.200	-.205	-.147	r
			•	•	ns	•	•	•	•	ns	p
			237	234	229	235	136	239	239	239	N
DO				.006	-.140	.020	.396	-.146	.404	.377	r
				ns	•	ns	•	•	•	•	p
				239	234	239	142	245	245	245	N
ln NH4					.119	.104	-.223	.599	-.172	-.064	r
					ns	ns	•	•	•	ns	p
					231	236	138	241	241	241	N
ln NN						.116	-.406	.103	-.023	-.041	r
						ns	•	ns	ns	ns	p
						231	134	236	236	236	N
ln PO4							.160	.139	.219	.152	r
							•	•	•	•	p
							140	241	241	241	N
D7FL GCR								-.276	.935	.999	r
								•	•	•	p
								144	144	144	N
D7FL CCPW									-.300	-.136	r
									•	•	p
									254	254	N
D7FL HWT										.890	r
										•	p
										254	N